A SHORT-RANGE PRECISE NAVIGATION SYSTEM

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THESIS

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December 1969

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A Short-Range Precise Navigation System

by

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ABSTRACT

A precise short-range relative navigation system has been proposed to provide repeatable position-determining capability of uniform accuracy over the entire area of coverage. It is a continuous-wave phase comparison system, which derives range information from the change in phase between stable oscillators as the distance between them is varied. The transmitters and their associated controls were designed to implement a prototype system. Considerations necessary in the development of the system receiver are discussed based on tests conducted on the transmitters.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

ACKNOWLEDGEMENT

Lieutenant Commander F. F. Mackenzie, USN, contributed significantly in the design and construction of several system components as well as several sections of this thesis. His technical expertise, imagination, tolerance, and patience were both extremely helpful and educational. Additionally, the practical experience of the Naval Postgraduate School Research and Development Staff were extremely helpful in transforming ideas into working circuits.

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I. SYSTEM DESCRIPTION

This thesis describes a passive accurate short-range navigation system similar to that which was first proposed by Lieutenant Dean, RCN, and further developed by Lieutenant Thomas, USN, [Refs. 1 and 2]. The system was primarily designed for precise local control of small surface vessels, but might be developed to cope with several short-range navigation problems. It is capable of uniformly precise fixes over the entire area of coverage with excellent repeatable position-determining capability.

The basic system consists of a Control Radio Transmitter, two or more Reflex Radio Transmitters in fixed locations, and a Mobile Radio Receiver. Each unit is controlled by its own stable oscillator. See Figure 1.1. The transmitters operate in a time-share mode at a single continuous-wave frequency. The Mobile Receiver sequentially monitors the transmitter and utilizes phase comparison of the transmitted signal and its own stable oscillator to determine the change of range from each transmitter. Each measurement yields a circular line of position representing points of equal phase, hence equal range about each transmitter. The distance between consecutive circles depends on the velocity of electro-magnetic propagation and the frequency of transmission. For example: using the velocity of light as 300 meters per microsecond (μs), at a frequency of 2.0 megahertz (MHz), each cycle represents a time lapse of 0.5 seconds or a

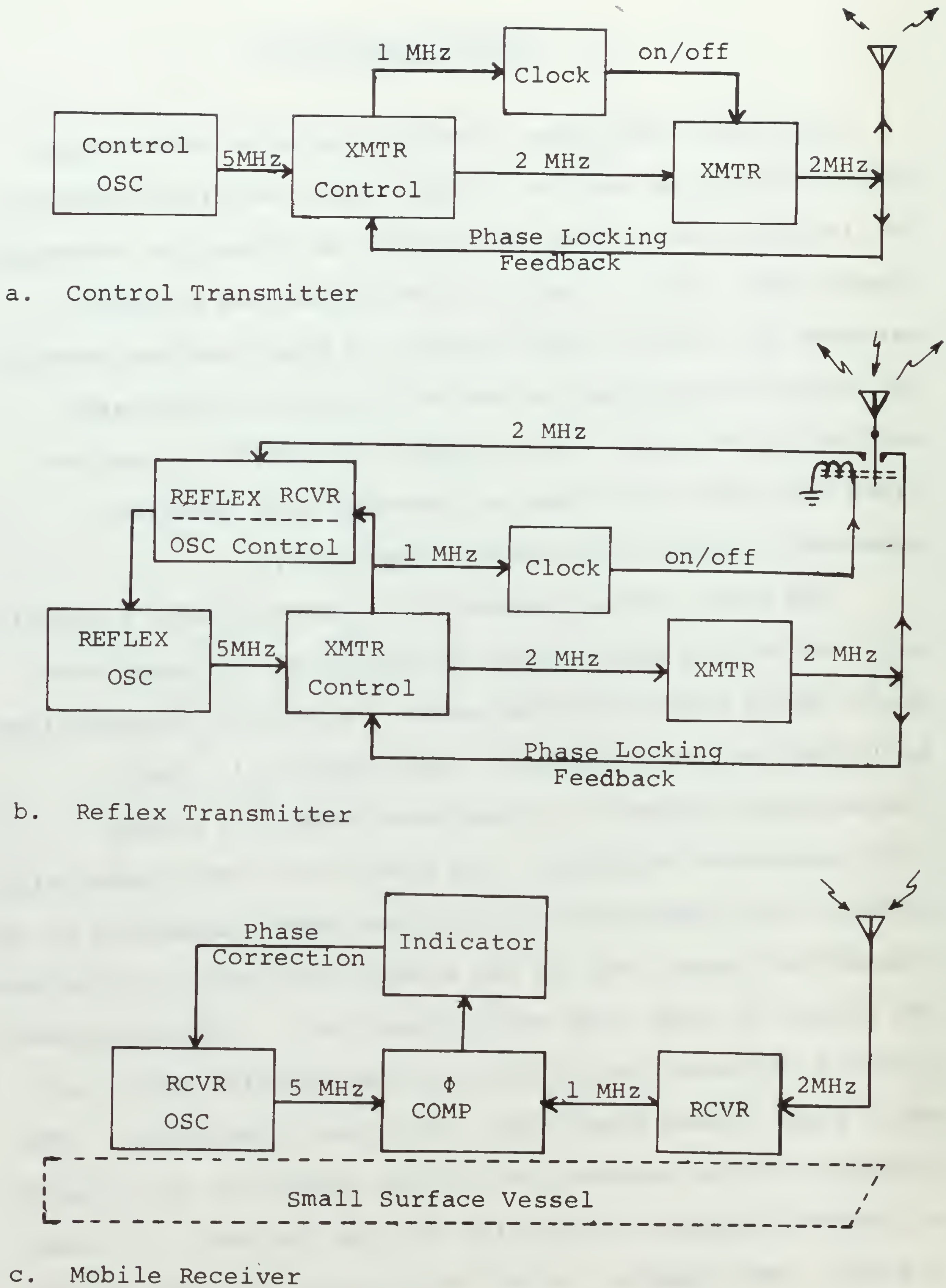

Figure 1.1. System Block Diagram

range interval between consecutive cycles of 150 meters. Ideally the transmitters would be placed such that the circular lines of position intersect at large angles over the intended area of coverage. See Fig. 1.2.

Since range measurement in this system is based on a phase comparison of two very stable oscillators, let it be assumed that these oscillators have no frequency error. Of course this is invalid, but the assumption will facilitate a description of the system. The signal of one oscillator transmitted to the other oscillator over a finite distance requires a finite time and is evidenced by an apparent change of phase of the transmitted signal proportional to the distance transmitted. The relative phase of the transmitted signal will be a constant at any point in space if the velocity of propagation is constant.[1] If phase comparison of the two oscillators were continuous and no phase change occurred over a period of time, it could be deduced that the distance between them had not changed. Conversely, if an increase or decrease of phase ($\Delta\Phi$) had occurred, the deduction would be that the oscillators had moved $\Delta\Phi$ cycles towards or away, respectively, from each other.

Note that no knowledge of original or final total phase between oscillators is available or necessary to determine

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[1] For a discussion of frequency errors associated with stable oscillators and variations in propagation velocity refer to paragraphs A. and F. of Section III.

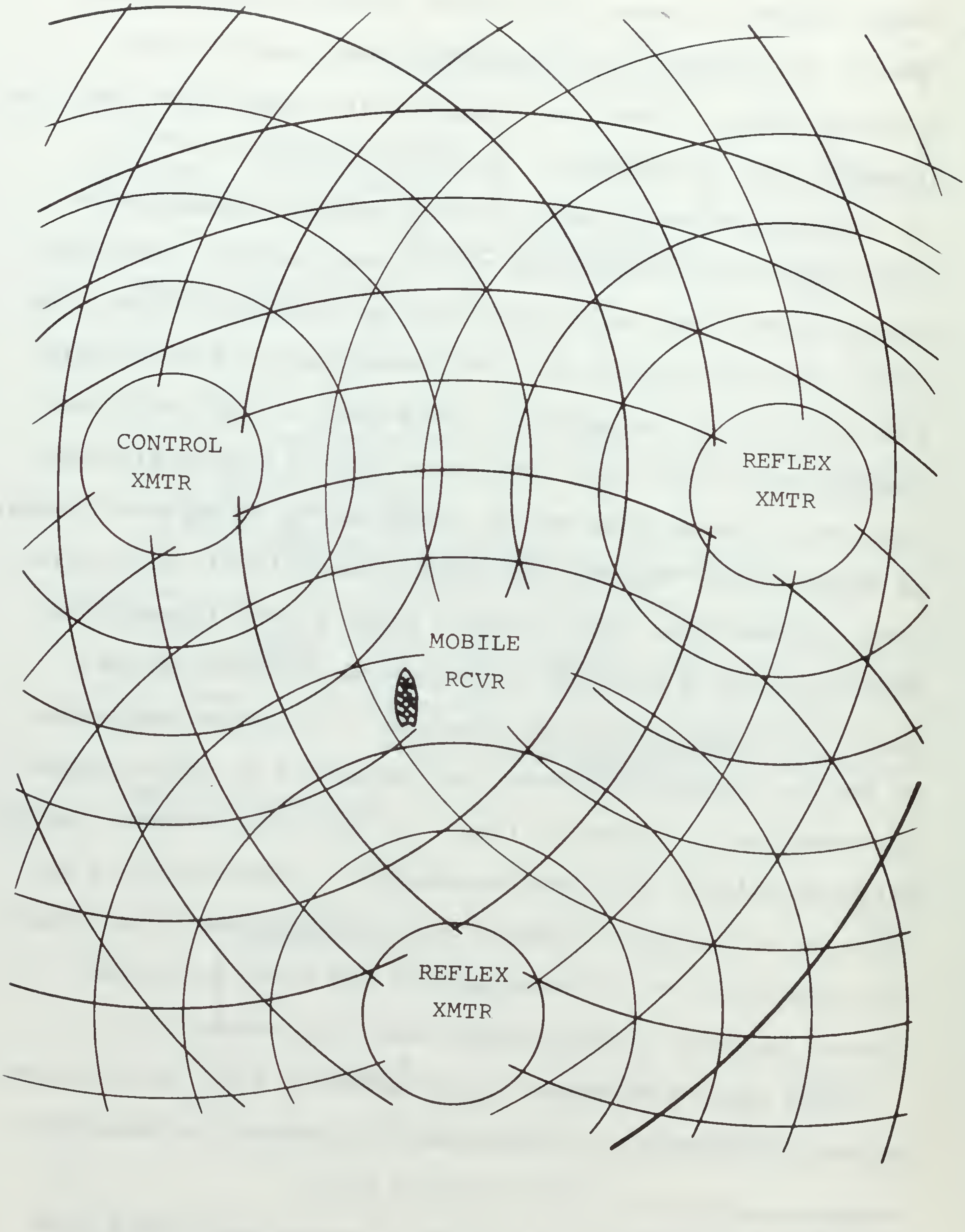

Figure 1.2. Transmitter Location

change of range. Of course, if phase difference is obtained at a reference position, subsequent measures of change of range can be projected to obtain present position.

Note also that phase is an ambiguous measurement, repeating every cycle. If continuous tracking of the oscillators is not possible, an ambiguity exists when more than one cycle can be traversed between measurements. This problem can be minimized by reducing the time between measurements, increasing the wavelength of the compared signals, or projecting an estimate of position based on relative velocity.

The Control Transmitter is the heart of this system providing the stability reference upon which all measurements are based. Its oscillator must, therefore, be as stable as is available to the system. The Reflex Transmitters and the Mobile Receiver, though phase locked and phase corrected respectively to the Control Oscillator, must have sufficiently stable oscillators to allow short-term navigation during a temporary loss of signal from the Control Transmitter.

Each transmitter alternately sends an unmodulated continuous-wave signal during its portion of the transmit cycle. The transmitted signal of the Control Transmitter is precisely controlled in phase by its own oscillator. While the Control Transmitter is sending, the Reflex Transmitters phase lock their oscillators to the phase established by the very stable Control Oscillator. With the transmitters broadcasting sequentially on the same frequency, spectrum is conserved and the receiver can remain tuned to the fixed system frequency. Transmitter identification is by signal duration, with the on/off keying controlled by a digital count of its own oscillator cycles. With stable clocks available at each transmitter, once each on/off cycle has been set no additional coordination need by provided.

The Mobile Receiver passively monitors the transmitters in sequence during the transmit cycle. The phase of its own stable oscillator is compared to that of each received signal. The received signals are of the same form as the transmitted signals except for the delay in passing from the transmitters to the Mobile Receiver. Changes in distance between the Mobile Receiver and each transmitter are manifest by changes in the apparent phase of the received signals. Measurement of change in phase and time rate of change thus provide measures of change of range and velocity of the Mobile Receiver relative to each transmitter.

The accuracy of a navigation system such as this depends primarily on the relative frequency stability of the oscillators used in the Control Transmitter and the Mobile Receiver. If the oscillators had a frequency offset of 2 parts in 10^{11}, the receiver would accumulate error at the rate of about 22 meters per hour.[2] This means that unless

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[2] These figures represent the values obtained by Dean during system stability tests using two Sulzer Model D-5 oscillators.

the Receiver Oscillator can be periodically compared to the Control Oscillator or unless much better oscillators are available, severe degradation in system accuracy results in a short time.

If this navigation system consists of three or more transmitters, the Mobile Receiver Oscillator can be corrected for any initial phase offset or slow oscillator drift. This is possible because all of the transmitters are phase locked to the Control Oscillator, and any offset present in the Receiver Oscillator results in a constant offset present in each phase measurement. With offset present, when a position determination (fix) is made, three arcs of position will form a triangle [Ref. 3]. See Fig. 1.3. Having a triangle, identical incremental corrections can be applied to each measurement until all the arcs pass through a common point. This common point is the unique convergence point which would have been obtained without phase offset. Furthermore, the total correction applied is precisely the amount of phase offset between the Mobile Oscillator and the Control Oscillator. An analytical development of this technique is presented in Section III.

Note that with the Reflex Oscillators phase-locked and the Mobile Receiver Oscillator corrected to the Control Oscillator during each transmit measurement cycle, the long-term system accuracy is dependent only on the stability of the Control Oscillator.

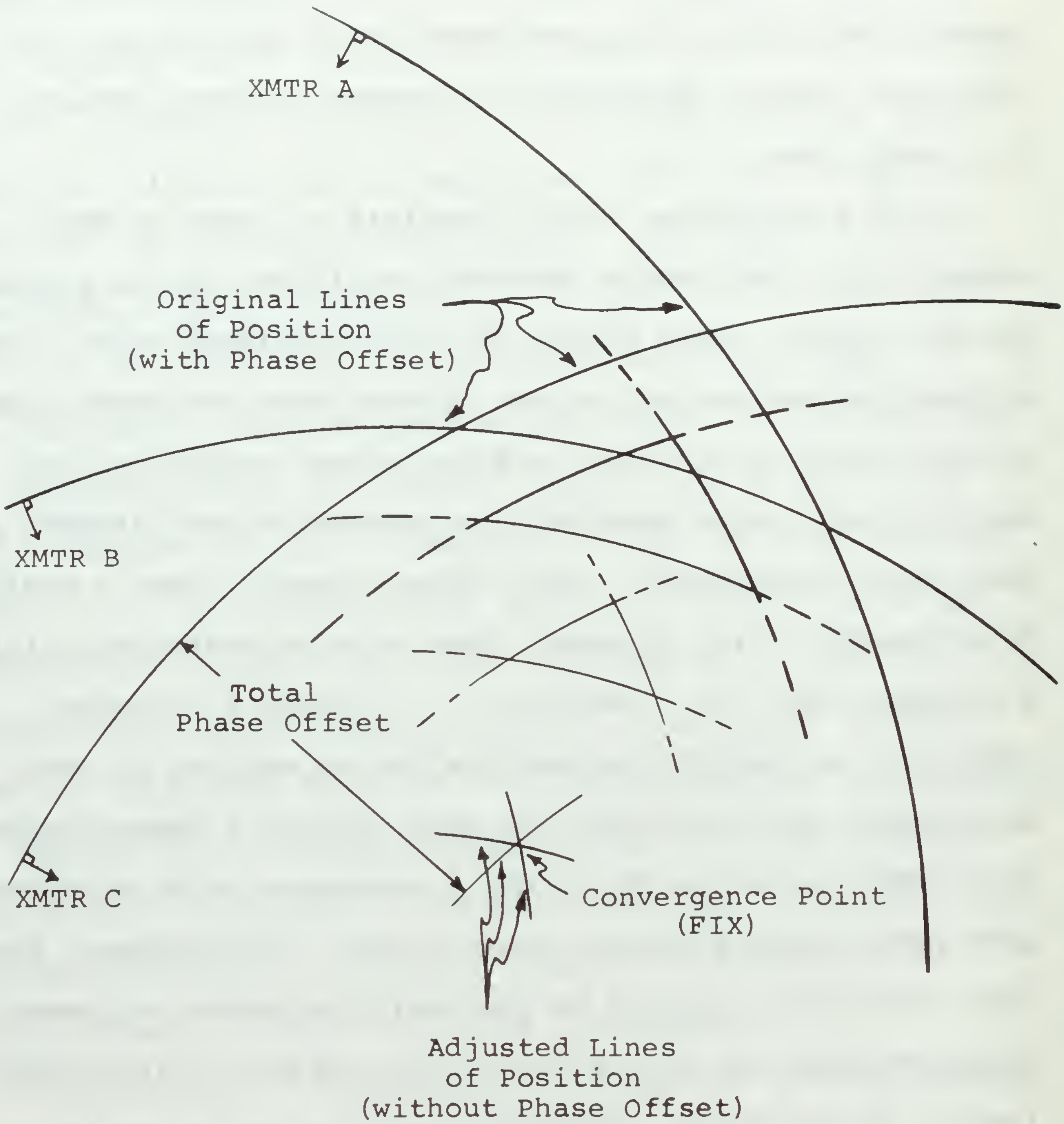


Figure 1.3. Mobile Receiver Phase Correction

Of course, any number of Mobile Receivers can make use of the system simultaneously without coordination and each remain entirely in a passive electronic configuration.

II. EQUIPMENT DESIGN

A. SYSTEM DESIGN

The system design basically follows the multi-transmitter, time-multiplexed, frequency-locked system recommended by Thomas with integrated circuits used wherever practicable.

A very accurate frequency standard with good long-term stability is used in the Control Transmitter as the system reference. The output signal of Control Transmitter is phase stabilized by a feedback loop to this Control Oscillator. This is necessary to minimize the effects of temperature or component change on the output signal.

In the Reflex Transmitter this same feedback control is used and the addition of a receiver allows its stable oscillator to be phase locked to the Control Oscillator. Of course, this method can be used with as many Reflex Transmitters as may be necessary in establishing a local navigation system. Several advantages to this method seem obvious. All the transmitters operate at exactly the same frequency. The offset of the Mobile Receiver Oscillator is the same with respect to all the transmitters and thus can be corrected. The use of a highly stable atomic standard becomes economically feasible in the establishment of a single Control Oscillator. (This subject is discussed in Section III.)

Every receiver has inherently a clock stable to within a few microseconds a day to provide control whenever accurate timing might be required.

In the prototype system designed for this feasibility study, a 2.0-MHz signal seemed desirable for several reasons. It lies near the top of the frequencies allocated for radio navigation [Ref. 4]. It is easily obtainable from most frequency standards available for this application. It is above the AM broadcast band, yet the wavelength allows the possibility of physically short antenna. At this frequency, stable ground waves can be expected for the range of the system, 30 to 50 miles. Also, this wavelength allows wide enough lanes that ambiguities can be dealt with for normal ships speeds and yet narrow enough that resolution to a few meters is not unrealistic.

1. Control Transmitter

The Control Transmitter, as shown in Fig. 2.1, uses a 2.0-MHz voltage-controlled oscillator (VCO), with phase stability provided by a 5.0-MHz Sulzer Model D-5 oscillator [Ref. 5]. The 5.0-MHz output from the Sulzer is fed into a synchronous digital divide-by-five circuit, where pulse propagation delay is minimized [Ref. 6]. The 2.0-MHz output from the transmitter is similarly divided by two. Both 1.0-MHz waveforms are compared in a phase detector, such as discussed in Section III. A dc output control voltage is produced proportional to the difference in phase between the two signals. This dc voltage level is applied to

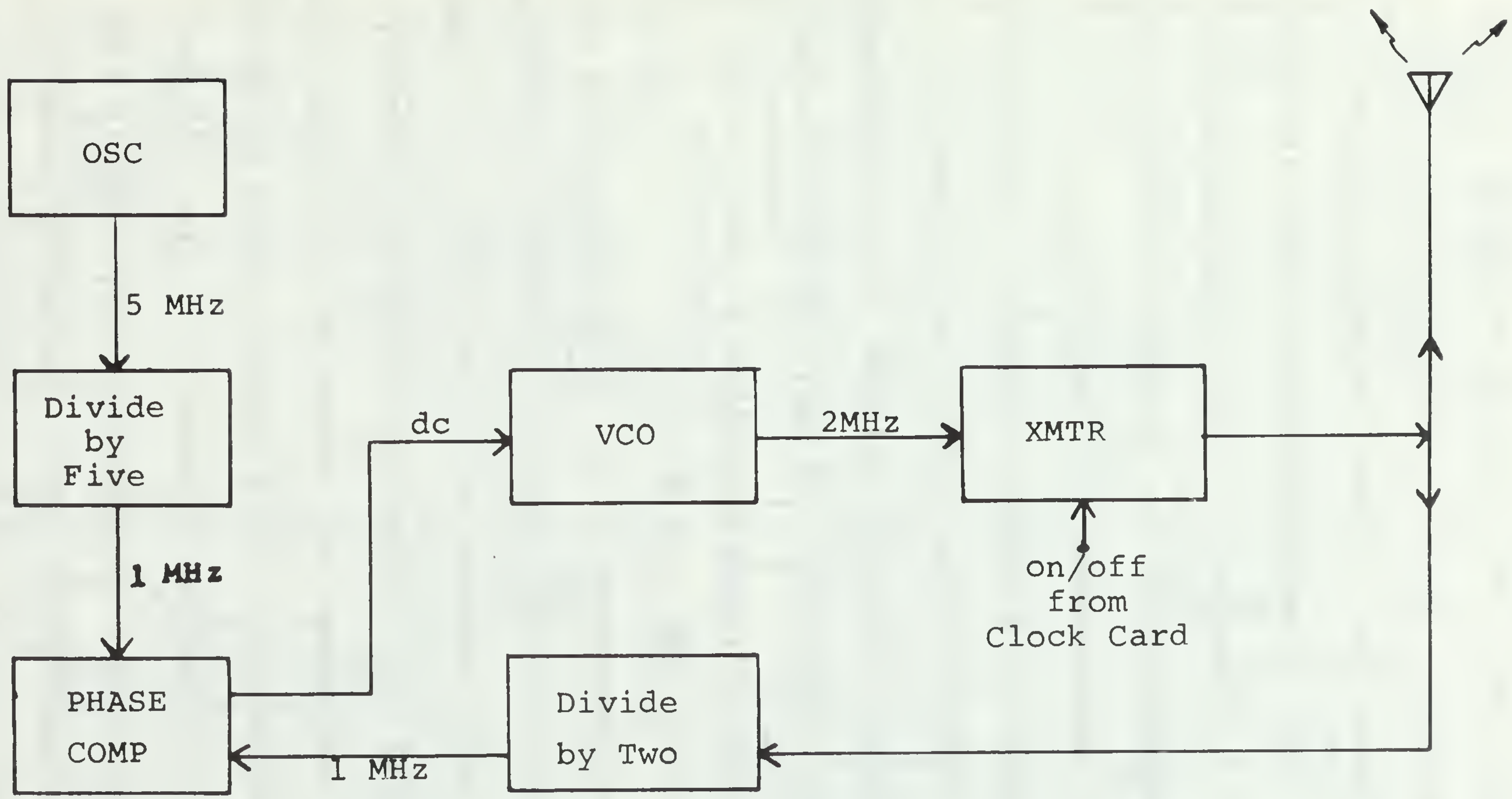


Figure 2.1. Transmitter Block Diagram

semi-conductor voltage-variable capacitors (Varicaps) in an LC network of the VCO to stabilize the the output frequency to the Control Oscillator and minimize variable effects on the transmitted signal. The VCO provides signal power to the transistor transmitter. Phase comparison might be done at any frequency, but it was convenient to use the highest common divisor of 2.0 MHz and 5.0 MHz Figures 2.2 and 2.3 show a control schematic and the assembled Control Card with dividing circuits, phase comparator and VCO.

Figure 2.4 shows the transmitter driver, final amplifier and method used in keying the transmitter on and off. The transmitter uses high-frequency silicon transistors operated Class C to improve efficiency. A lamp, which is normally shorted during operation, was installed to protect the transistors during initial tuning.

The low output impedance of the final transistor is matched to a 6-ohm load (the antenna discussed in Section IV) using a double-pie network with a designed Q of twenty.

Actual keying of the transmitter is accomplished by keeping the final amplifier and driver on a floating ground. To turn the transmitter on, the floating ground is shorted to true ground. The transmitter schematic of Fig. 2.4 was built on one Transmitter Card as shown assembled in Fig. 2.5.

Timing of the transmitter keying is accomplished by logic circuits. A 1.0-MHz signal, derived from the stable oscillator, is fed into a counting mechanism consisting of 24 bistable multivibrators (flip-flops). The flip-flops divide

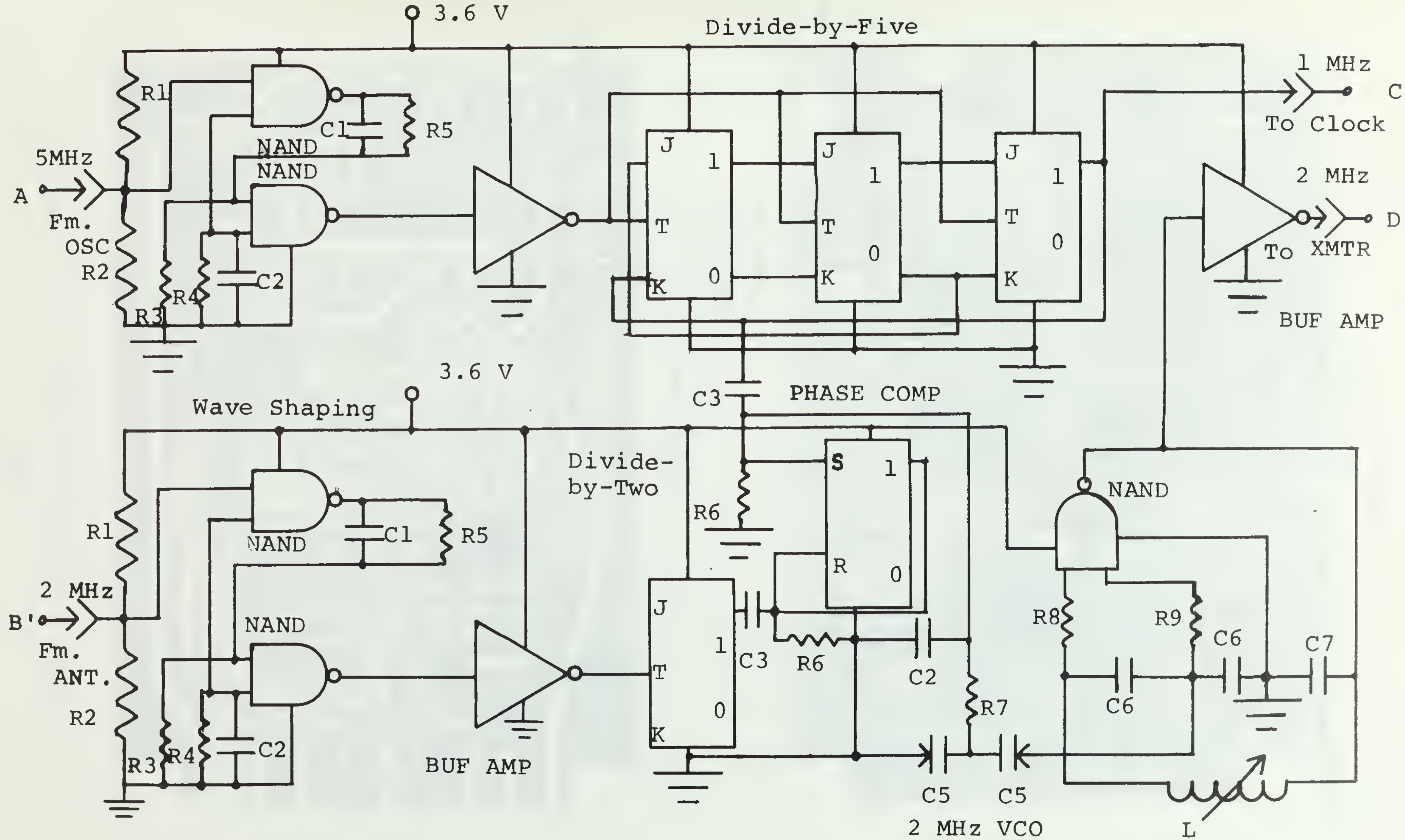


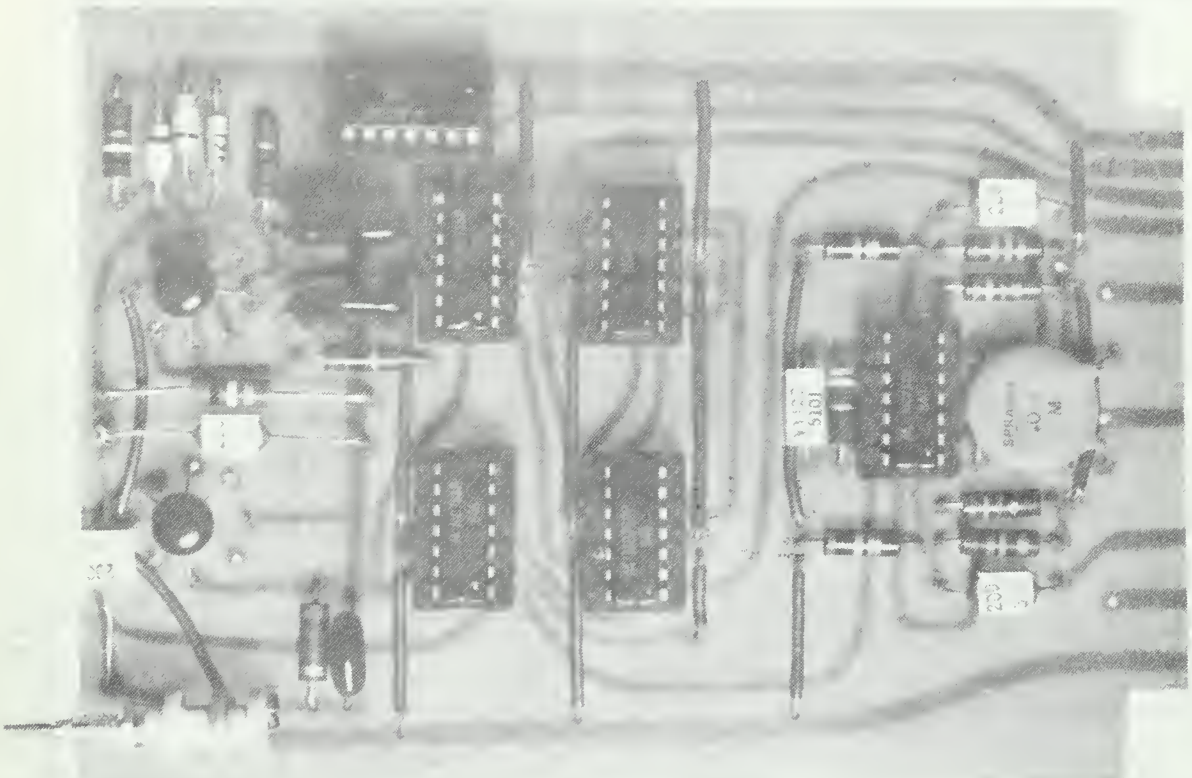
Figure 2.2. Transmitter Control Schematic

TABLE I

Transmitter Control Card Components List

Component	Value
R_1	20,000 Ω
R_2	12,000 Ω
R_3	6,800 Ω
R_4	270 Ω
R_5	3,900 Ω
R_6	51 Ω
R_7	20,000 Ω
R_8	220 Ω
R_9	100,000 Ω
C_1	51 Ω
C_2	.01 Ωf
C_3	2,000 pf
C_4	VARICAPS
C_5	200 pf
C_6	470 pf
L	VARIABLE
NAND GATES	MC 790
BUF AMP	MC 788
FREQ. DIVIDERS	MC 790
RS FLIP-FLOPS	MC 724

Front View



Rear View

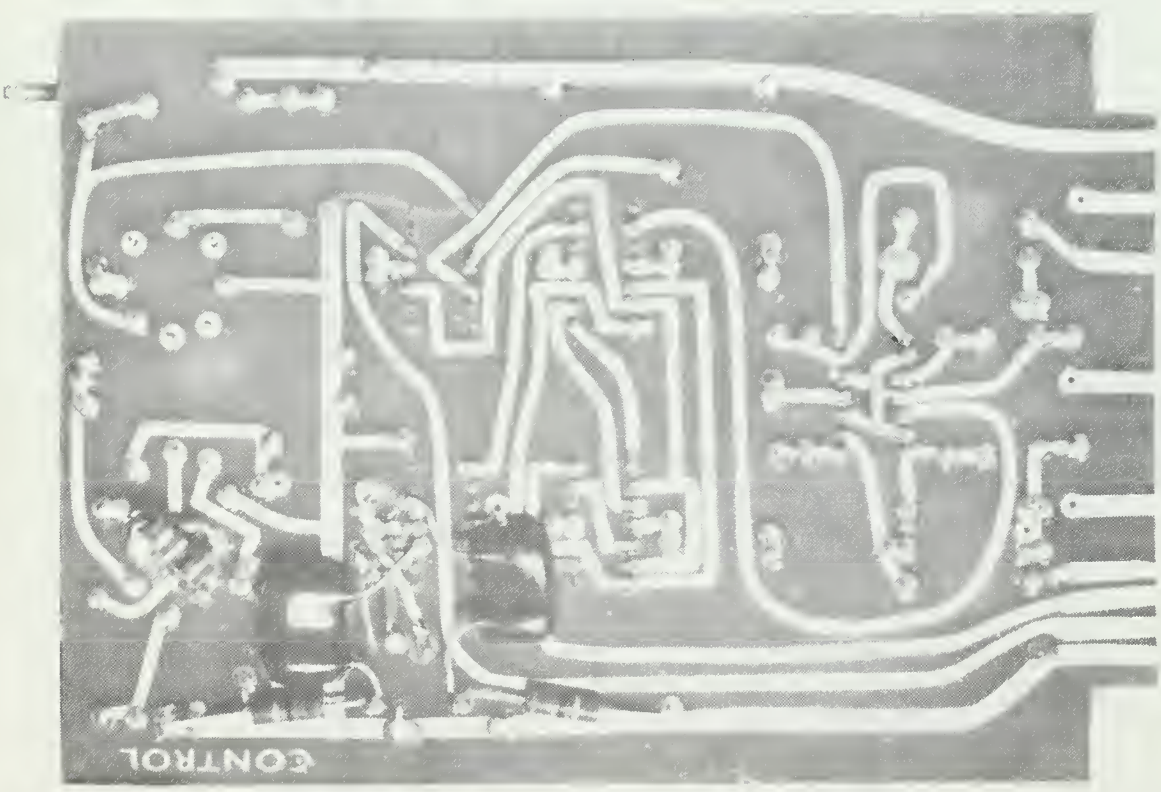


Figure 2.3. Transmitter Control Card

Table II

Transmitter Driver and Final Amplifier Components List

Component	Value
R_1	12,000 Ω
R_2	3,000 Ω
R_3	100 Ω
R_4	150 Ω
R_5	56 Ω
C_1	270 pf
C_2	.01 μf
C_3	.1 μf
C_4	.002 μf
C_5	.02 μf
C_6	550-1600 pf
C_7	.003 μf
C_8	.007 μf
C_9	550-1600 pf
C_{10}	2 pf
L_1	3.6 μh
L_2	3.5 μh
T_1	2N2102
T_2	2N3705

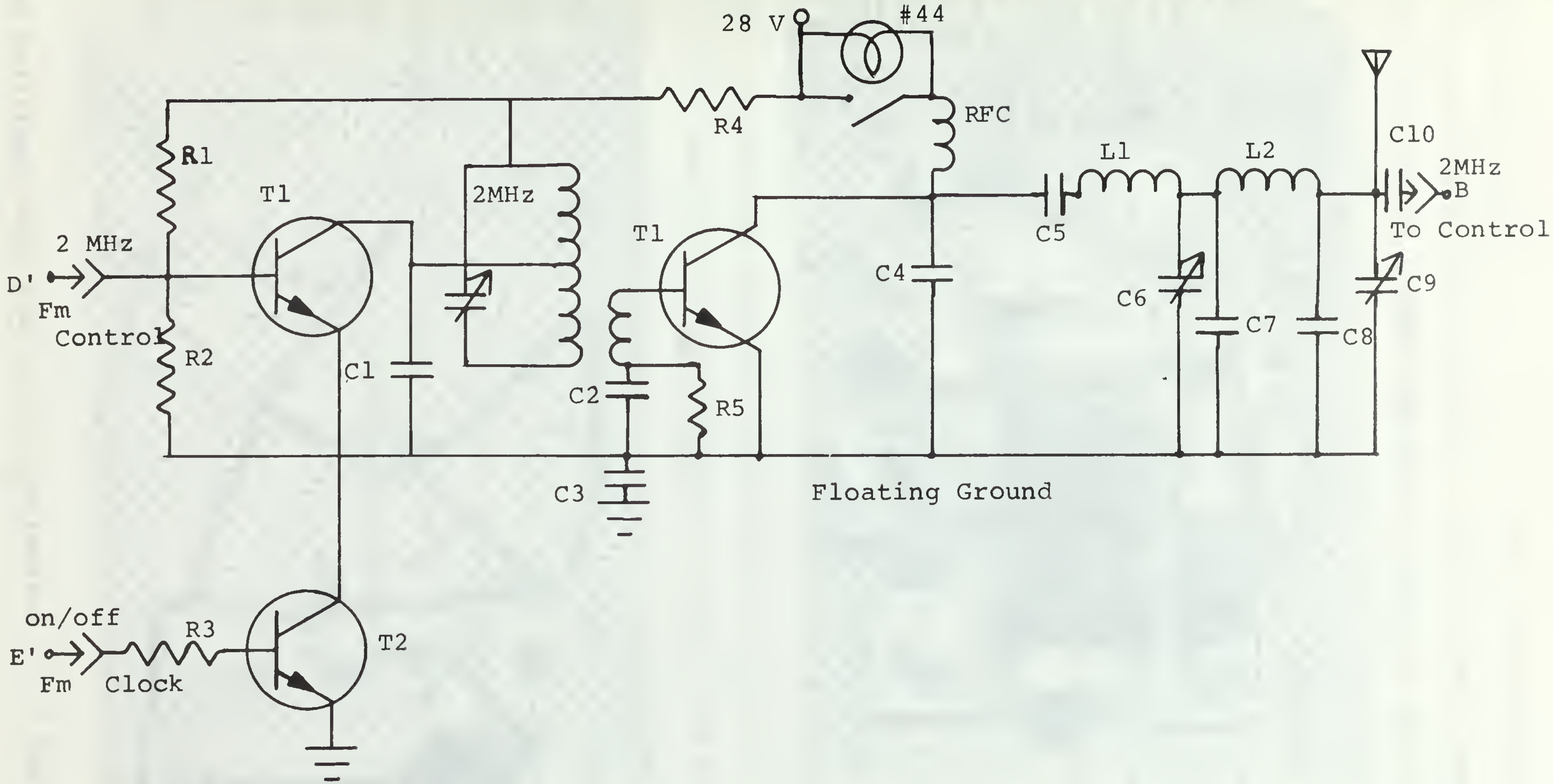
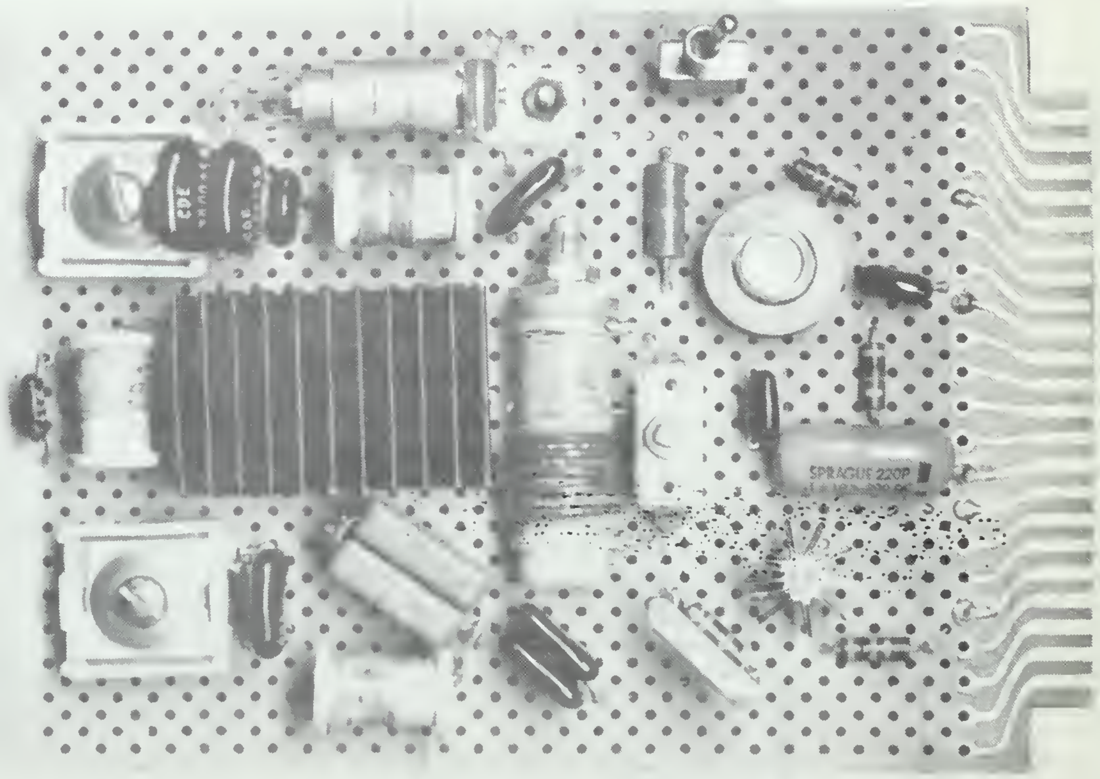


Figure 2.4. Transmitter Driver and Final Amplifier Schematic

Front View



Rear View

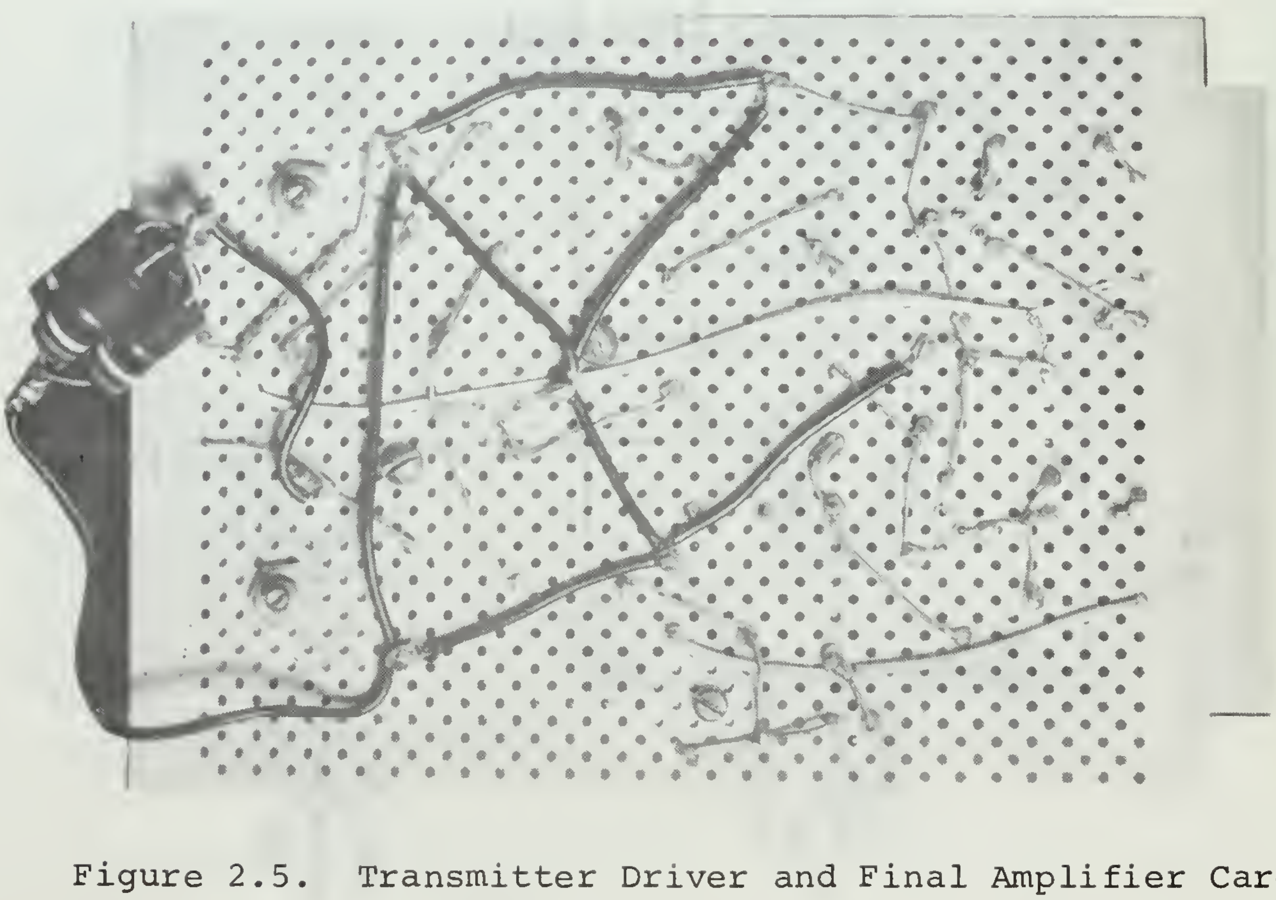


Figure 2.5. Transmitter Driver and Final Amplifier Card

the 1.0-MHz signal by 2^{24} (16,777,216) and provide "0" and "1" logic-level output signals. Using various combinations of the flip-flop outputs the on/off cycle of the transmitters is controlled as shown on the Clock Card logic diagram, Fig. 2.6. The transmitter is turned off with a "1" logic-level signal either from the 24th flip-flop or from a special combination of flip-flop outputs. The combination of outputs used to turn off the Control Transmitter can be described as $[(20+21)\cdot22] \cdot 23+24$. Standard logic notation is used where "+" represents "or" and "·" represents "and" [Ref. 7]. The Control Transmitter then is off for 11,010,048 counts and on for 5,767,168 counts. At a counting rate of 1.0 MHz this gives directly the duration of the on and off cycle in microseconds. The Reflex Transmitters are similarly keyed with one station using the combination $(21\cdot22\cdot23) + 24$, on 5.242880 seconds and off 11.534336 seconds, and the other station using the combination 23+24, on 4.194304 seconds and off 12.582912 seconds. The time when all transmitters are off, 1.572864 seconds, is more than adequate separation between stations. For example: Suppose one transmitter commences transmission 500 milliseconds after another shuts off. Further, suppose the transmitters are 50 miles (309 μs) apart. In this case, the transmitters would have to drift in opposite directions 499,691 cycles before foldover could result. This amount of drift would have previously rendered the system inoperative. In practice, the reflex station clocks were started by hand with any audible gap between

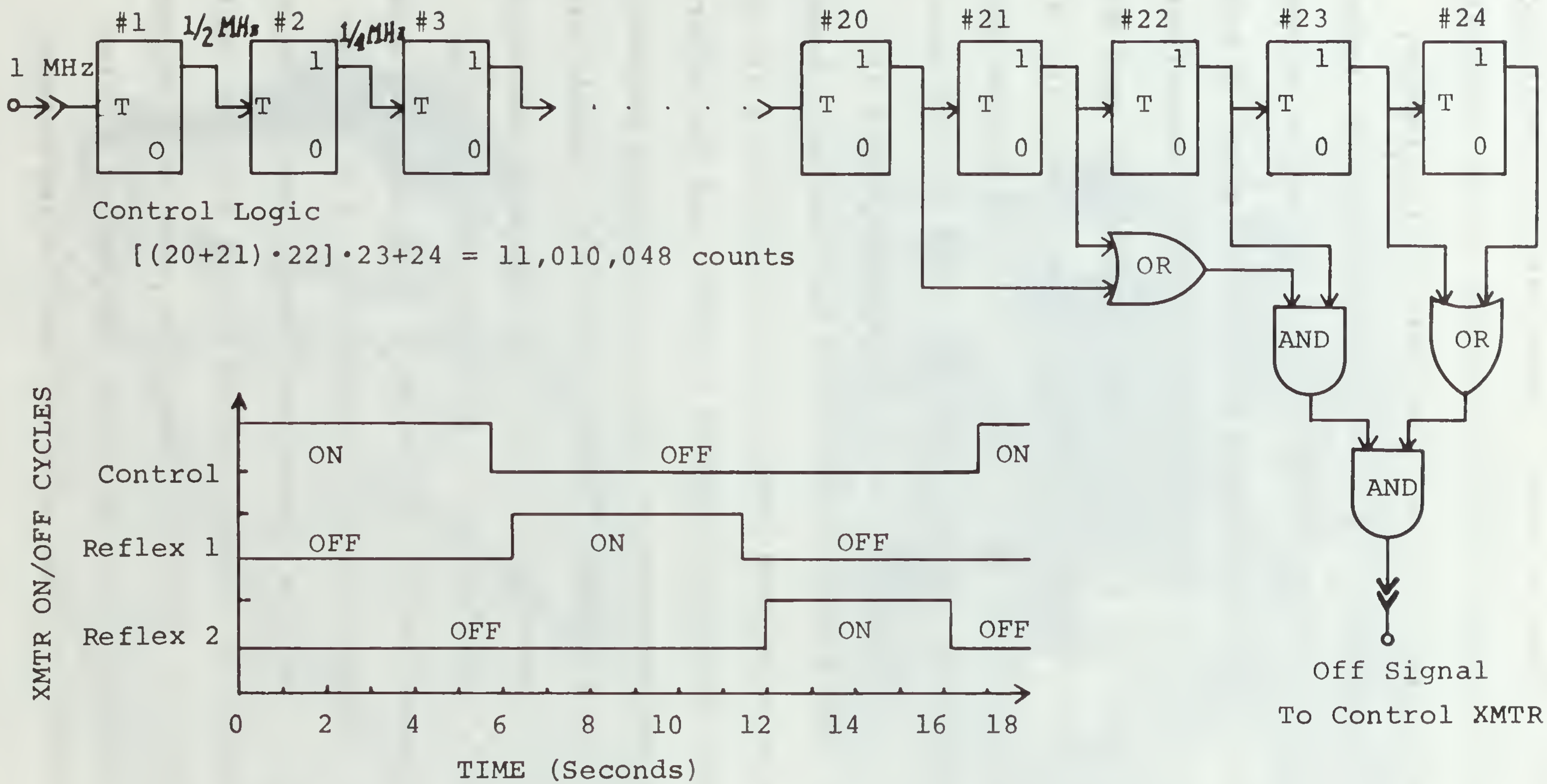
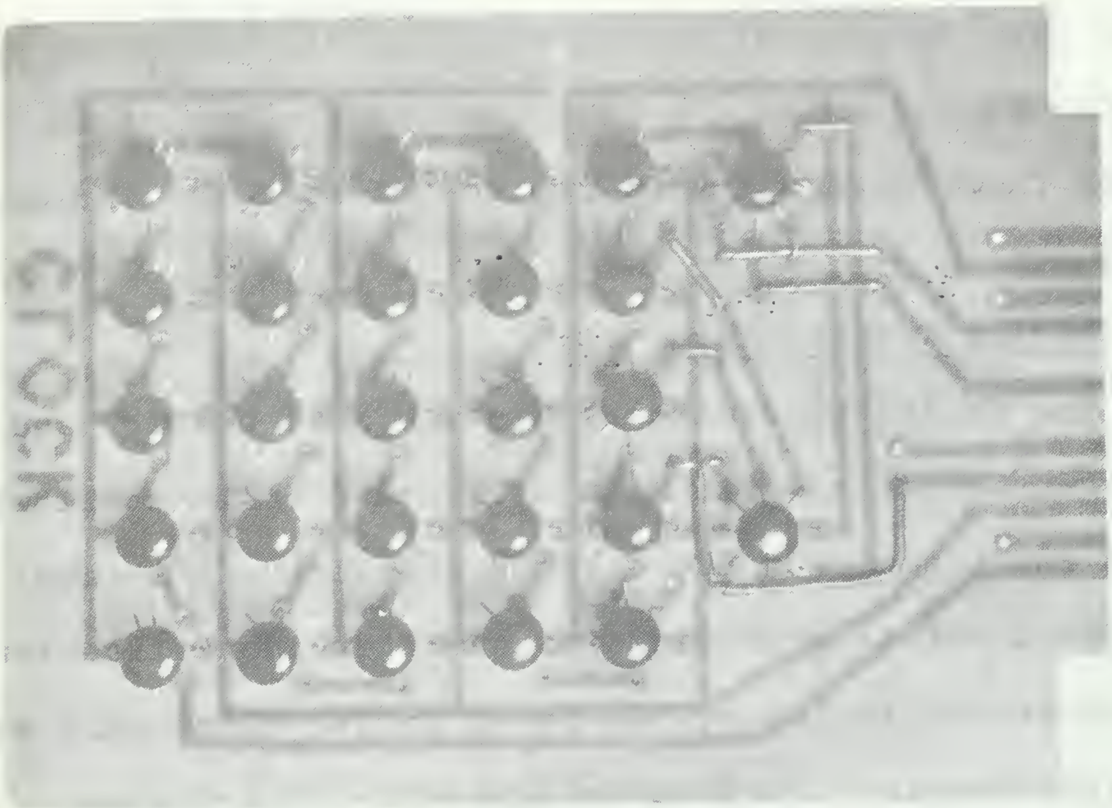


Figure 2.6. Control Clock Logic Diagram and Transmitter On/Off Cycles

Front View



Rear View

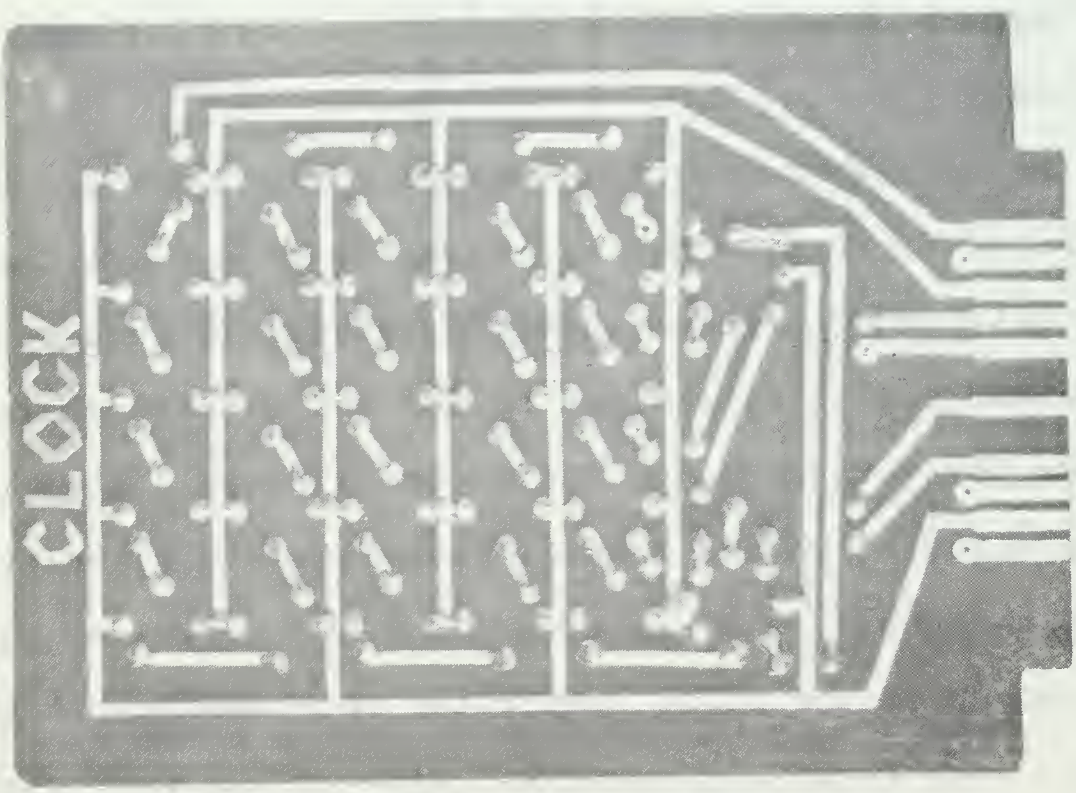


Figure 2.7. Clock Card

signals providing adequate separation. Of course, other logic combinations could be used where the number of stations being used and the relative velocity of the mobile receiver are just two of the considerations that would be made. Figure 2.7 shows the front and rear views of an assembled Clock Card using Fairchild "Micrologic" Integrated Circuits.

2. Reflex Transmitters

The Reflex Transmitters use the same Control and Transmitter Cards shown in Figs. 2.3 and 2.5, thus allowing complete interchange of these cards in all transmitters. Since signal duration provides transmitter identification, each transmitter in the system has a unique Clock Card wiring. Interchanging Clock Cards similarly interchanges transmitter identification.

The Reflex Transmitter has a receiver and oscillator control system shown in block diagram in Fig. 2.8 and schematically in Fig. 2.9.

As in the transmitter, on/off control timing of the Reflex Receiver is provided by its associated Clock Card so that only the Control Transmitter signal is received. The received signal is divided by two and phase compared to a 1.0-MHz derivative of the Reflex Oscillator. After the received signal from the Control Transmitter has achieved a preset threshold, one series of 64.0-MHz pulses is gated by the output of the phase comparator into a five-bit shift register. The threshold detector only insures that noise

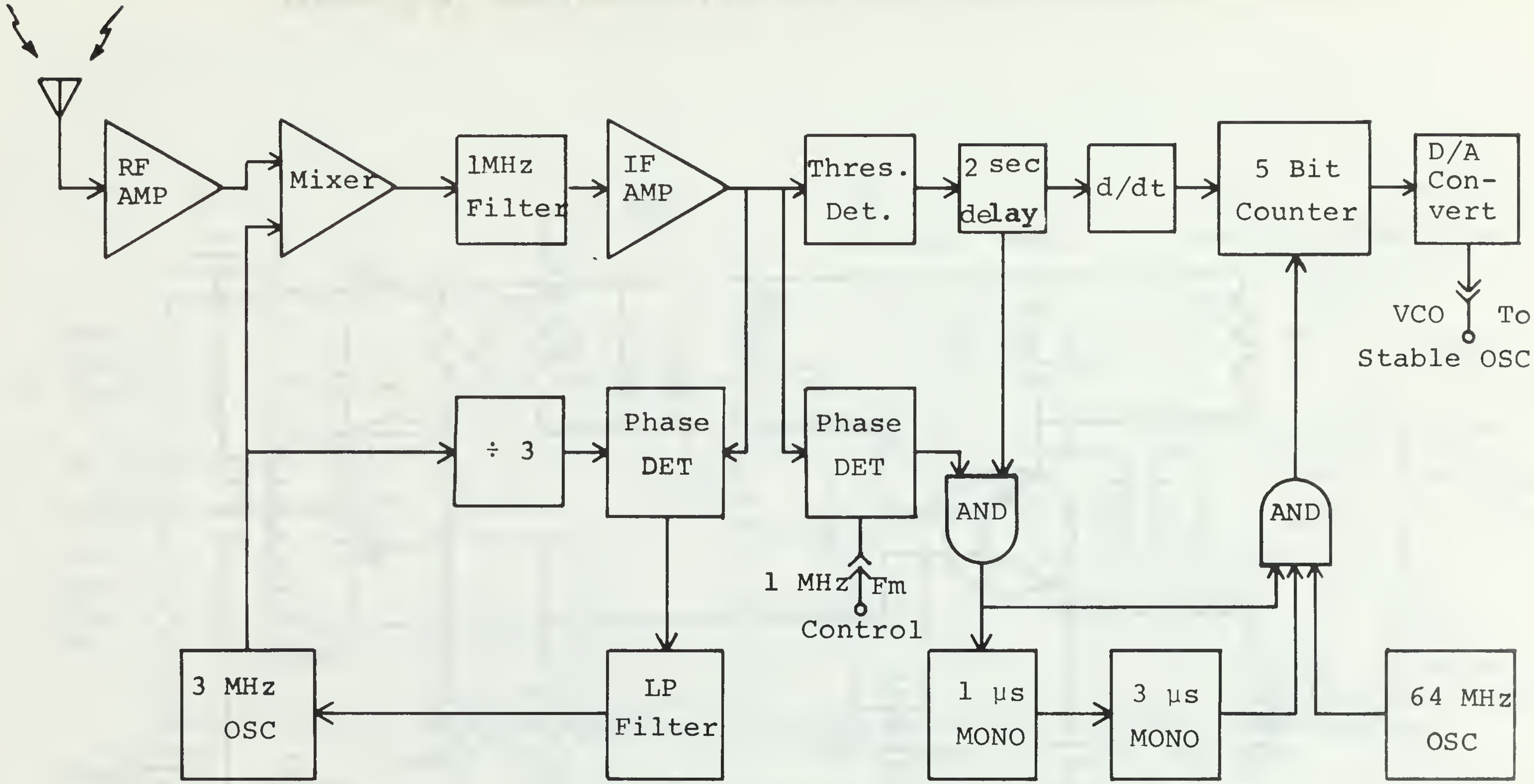


Figure 2.8. Reflex Receiver and Oscillator Control Block Diagram

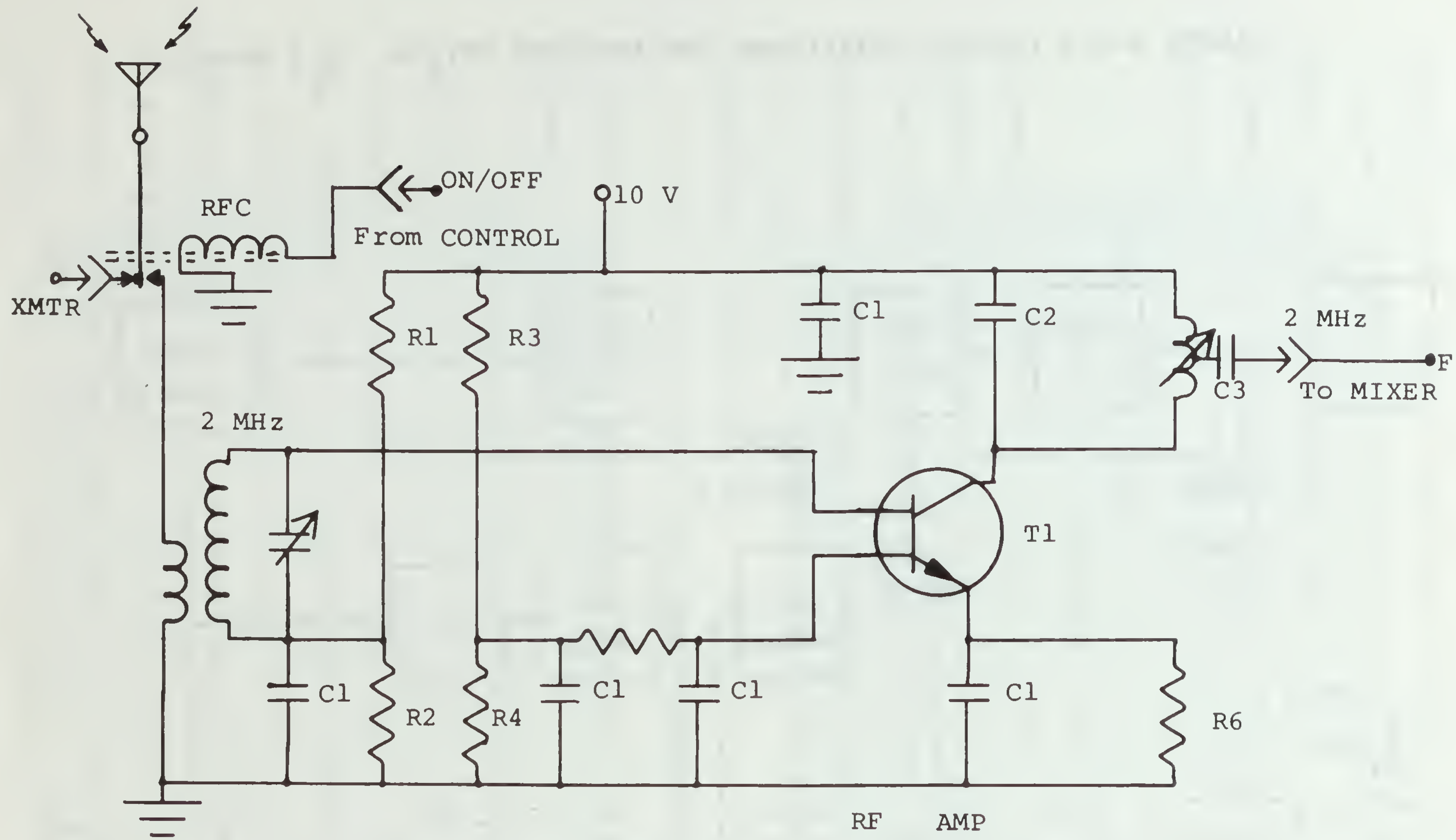


Figure 2.9. Reflex Receiver and Oscillator Control Schematic

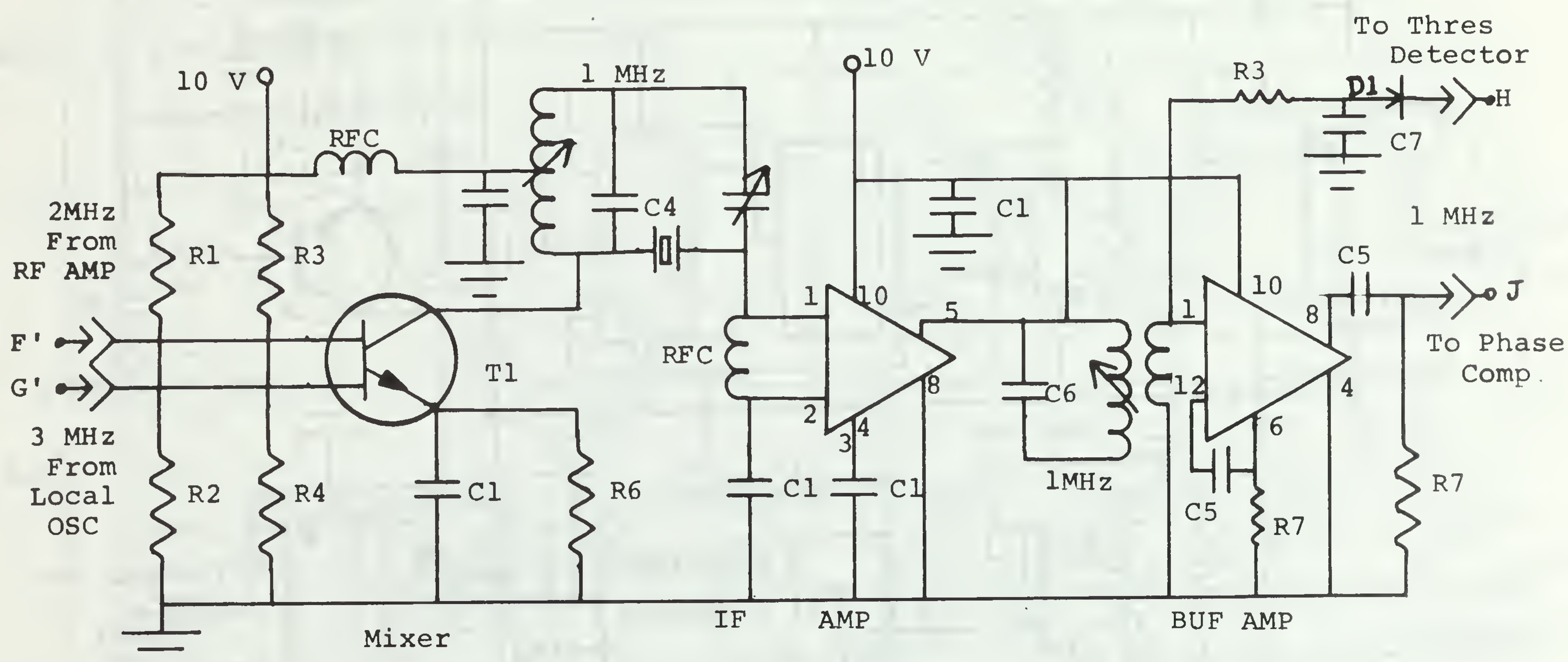


Figure 2.9. Reflex Receiver and Oscillator Control Schematic (Continued)

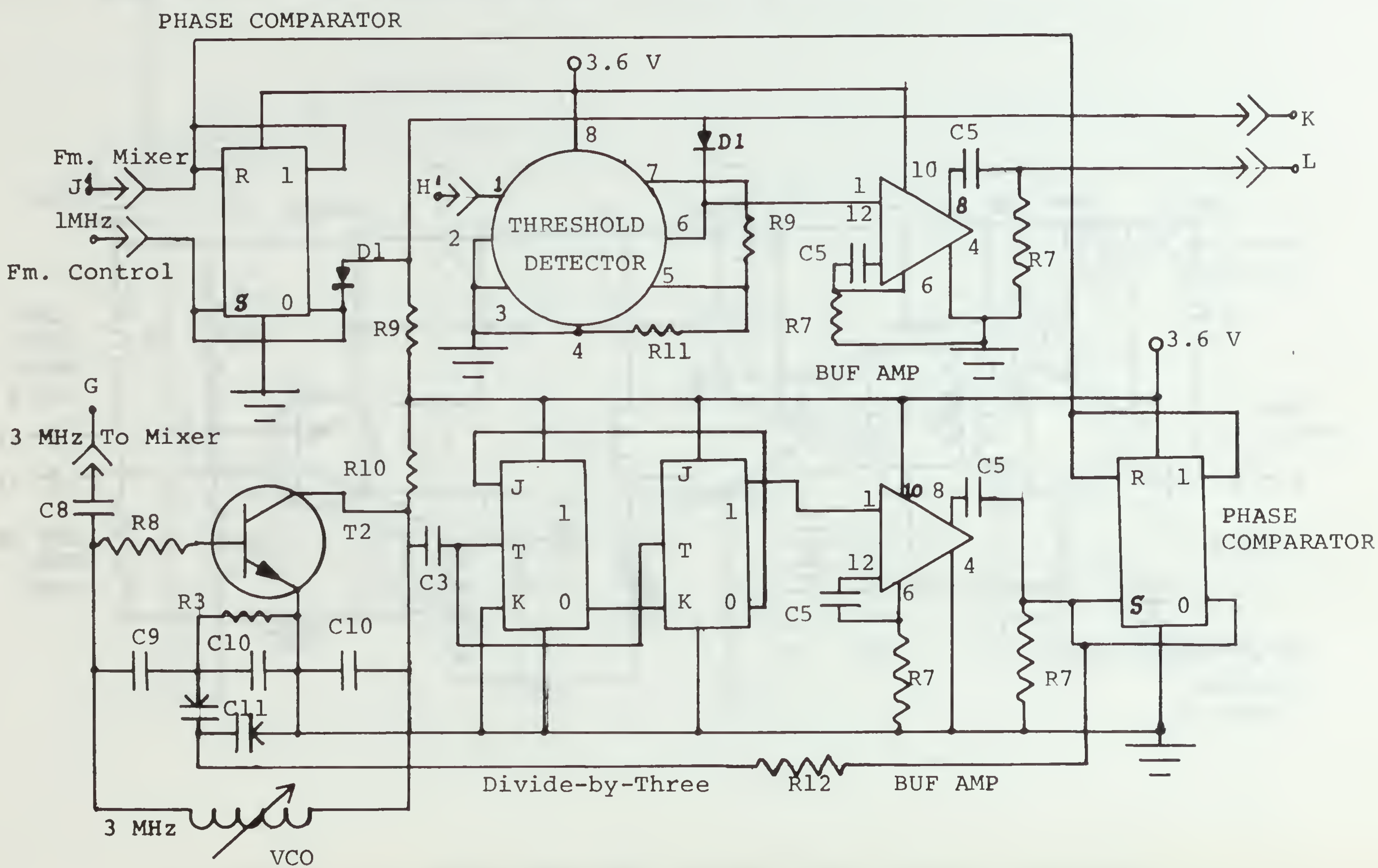


Figure 2.9. Reflex Receiver and Oscillator Control Schematic (Continued)

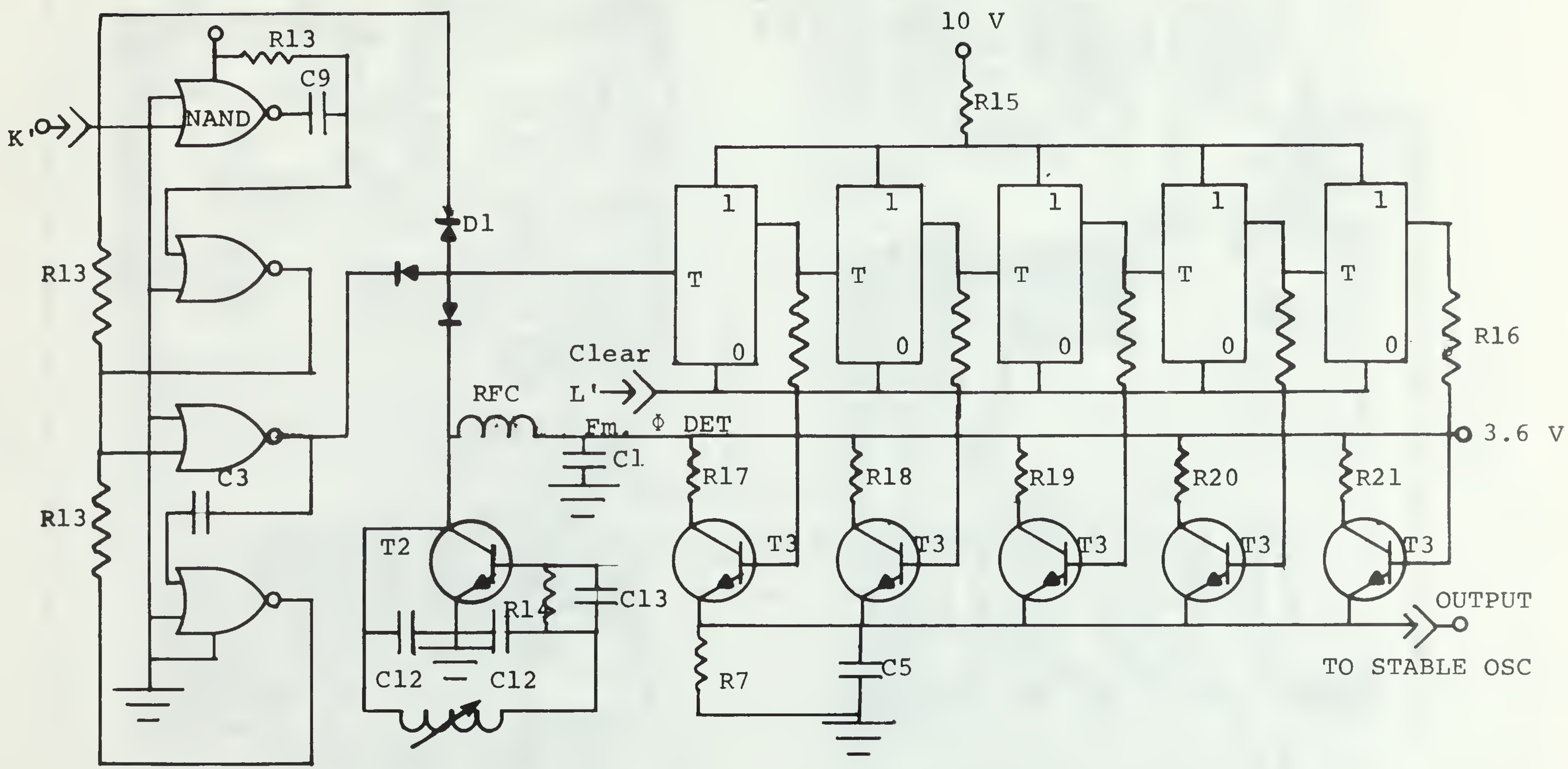


Figure 2.9. Reflex Receiver and Oscillator Control Schematic (Continued)

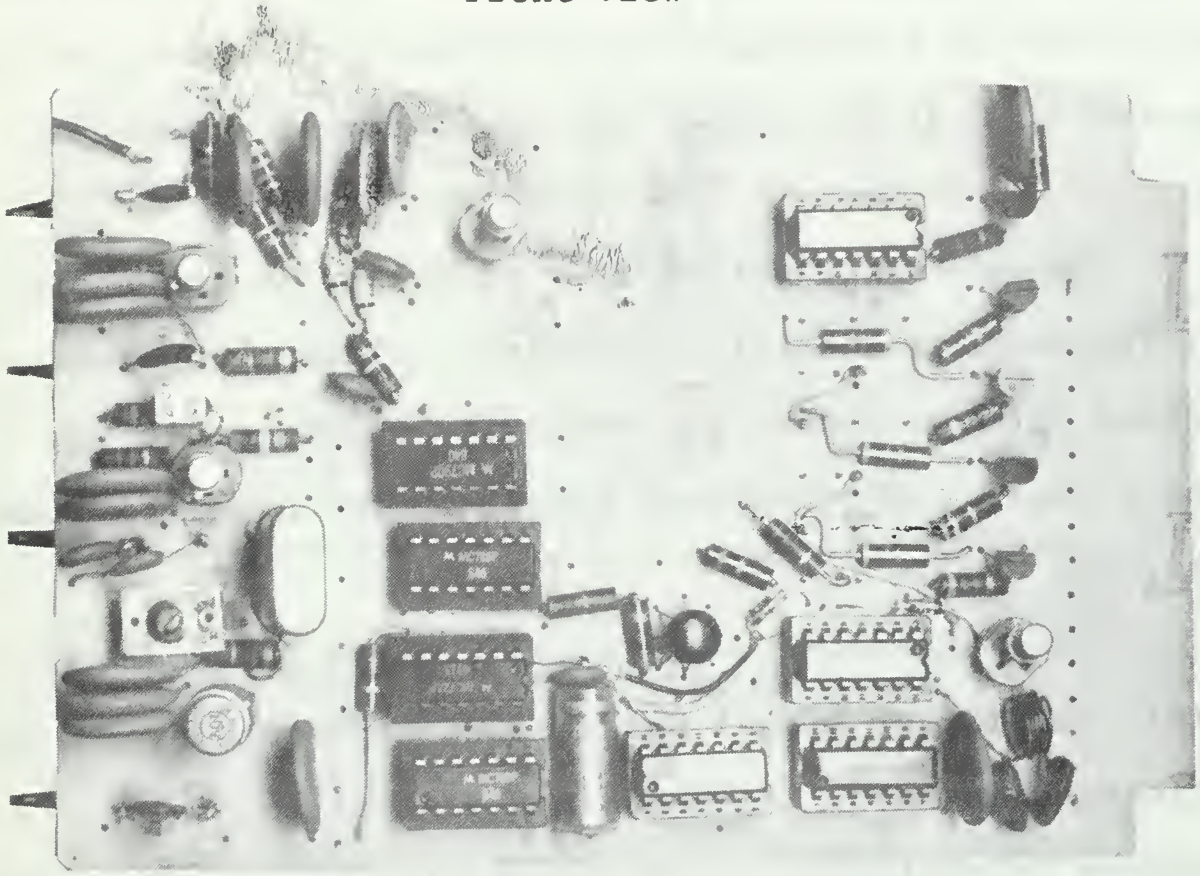
Table III

Reflex Receiver and Oscillator Control

Card Components List

Component	Value	Component	Value
R_1	150,000 Ω	C_1	.01 μf
R_2	27,000 Ω	C_2	100 pf
R_3	100,000 Ω	C_3	200 pf
R_4	33,000 Ω	C_4	--
R_5	1,800 Ω	C_5	2,000 pf
R_6	270 Ω	C_6	--
R_7	51 Ω	C_7	30 μf
R_8	20,000 Ω	C_8	5 pf
R_9	1,000 Ω	C_9	540 pf
R_{10}	220 Ω	C_{10}	250 pf
R_{11}	1,200 Ω	C_{11}	V56E
R_{12}	200,000 Ω	C_{12}	10 pf
R_{13}	6,800 Ω	C_{13}	25 pf
R_{14}	5,600 Ω	D_1	1N4009
R_{15}	55 Ω	T_1	3N141
R_{16}	300 Ω	T_2	2N708
R_{17}	8,000 Ω	T_3	2N3705
R_{18}	4,000 Ω		
R_{19}	2,000 Ω		
R_{20}	1,000 Ω		
R_{21}	500 Ω		
IF AMP	CA 3012		
BUF AMP	MC 788		
PHASE COMP.	MC 724		
THRES. DET.	RCA 914		
÷ 3	MC 790		
SHIFT REG.	MC 1013P		
NAND	MC 724		

Front View



Rear View

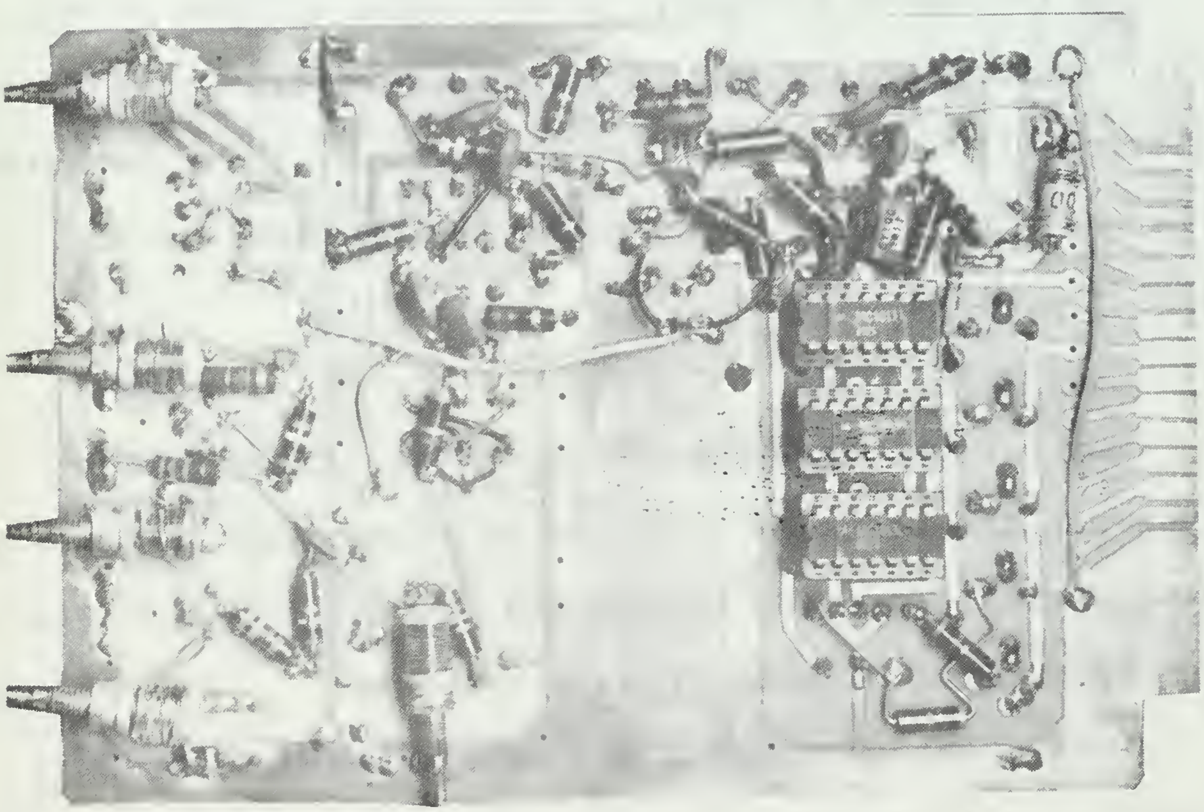


Figure 2.10. Reflex Receiver and Oscillator Control Card

does not prematurely clear the shift register. The output of the shift register is converted to an analog dc voltage which is fed to a varicap in the Reflex Oscillator providing frequency control and completing the feedback phase-lock loop.

Note that a count of 9 or 41 pulses in the short shift register is entirely equivalent. This is an intentional device used to remove the ambiguity which results in dividing the 2.0-MHz received signal by two prior to phase comparison.

Since the shift register is cleared only when the Control Transmitter Signal has reached a preset level, the last reading is held. Although the digital to analog conversion is nonlinear, it is monotonic and provided good frequency control on the Sulzer oscillators used.

As indicated earlier, in the event of loss of the Control Transmitter all the Reflex Transmitters would continue to function within the stability provided by their own stable oscillators. Figure 2.10 shows the Reflex Receiver and Oscillator Control Card.

3. Mobile Receiver

The design, development, and test of the Mobile Receiver was the basis of a thesis by Thomas and is briefly discussed here to provide background and continuity. Figure 2.11 shows a block diagram of this receiver.

Throughout the design and development of this receiver the all-important concern was phase stability, with

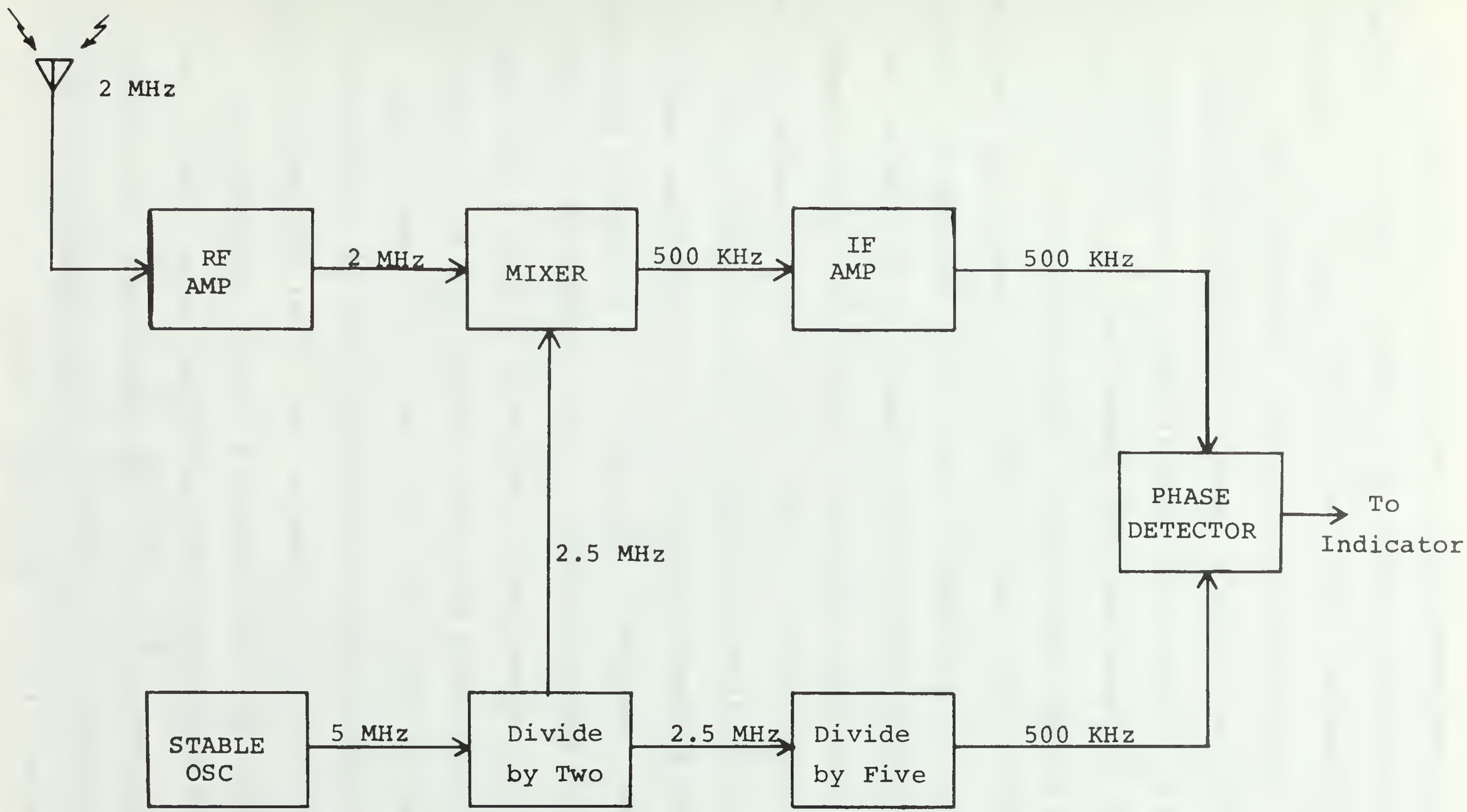


Figure 2.11. Mobile Receiver Block Diagram

selectivity and sensitivity desirable but secondary. A certain phase shift through the receiver circuits was expected, and if constant could be corrected while at a reference position. The problem was change in frequency with age, temperature, and physical shock. It is here that phase stability and selectivity were at odds. The narrower the bandwidth, the more rapid the phase change with a change in frequency brought about by the above conditions.

The problem was circumvented by developing a Receiver Phase Test Circuit shown in Fig. 2.12. The test VCO output was connected directly to the primary of the antenna coil. Any resulting phase output was due entirely to the phase shift in the receiver circuits. Periodically conducting the test on the receiver provided the internal phase shift present and allowed correction to the total phase readout.

The test circuit appeared to be successful in trials conducted by Thomas and led to the recommendation of additional filtering and amplification to improve signal sensitivity. As designed the signal sensitivity of the receiver was limited to about 25 μV with very low dynamic range. Of course, it must be kept in mind that the test circuit requires that changes of phase be small over the period of time between tests and that cascading filters increases the possibility of greater rates of phase change. Though the test circuit was able to provide corrections for internal phase shifts due to the receiver circuit components, it could not determine relative oscillator offset.

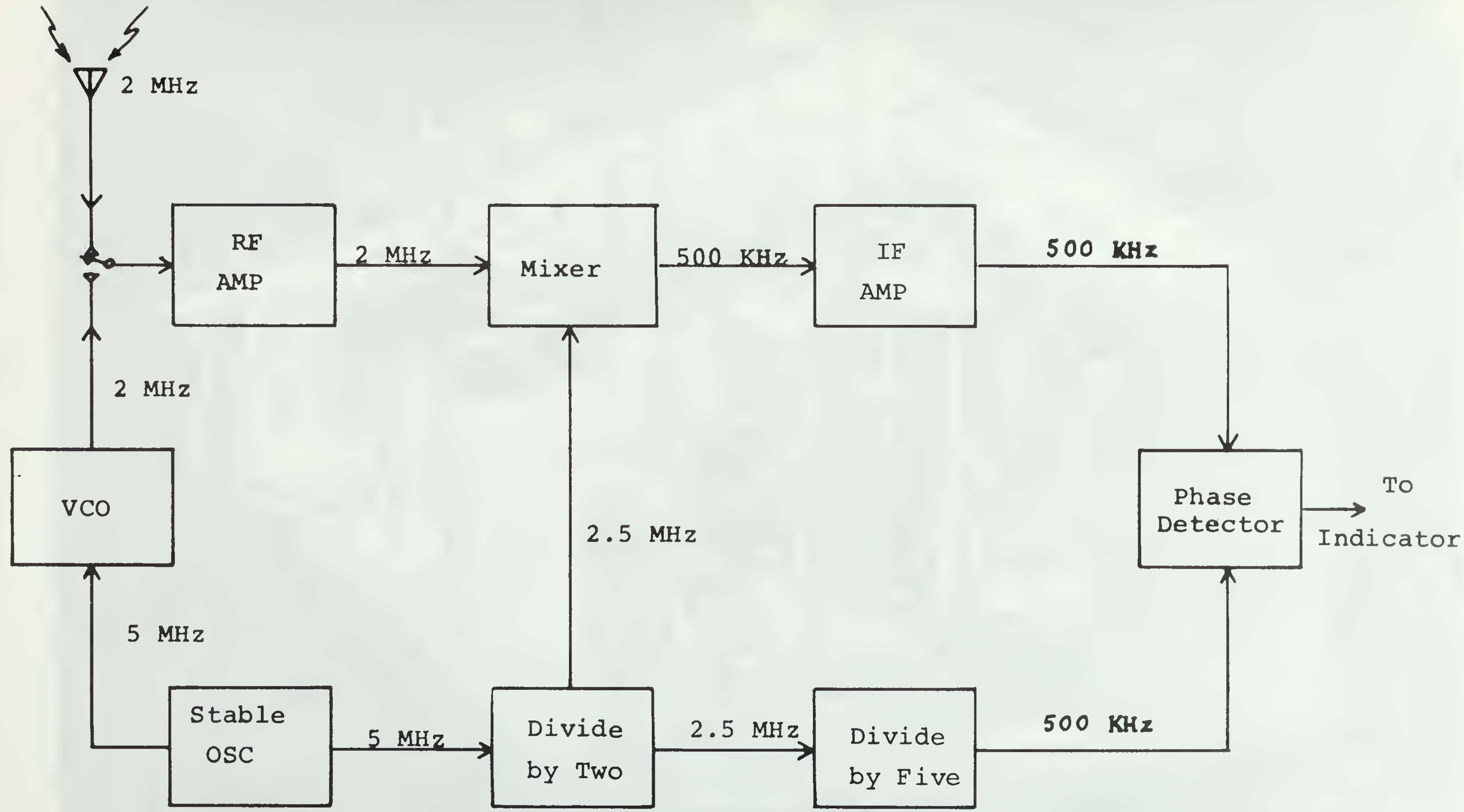


Figure 2.12. Receiver Test Circuit

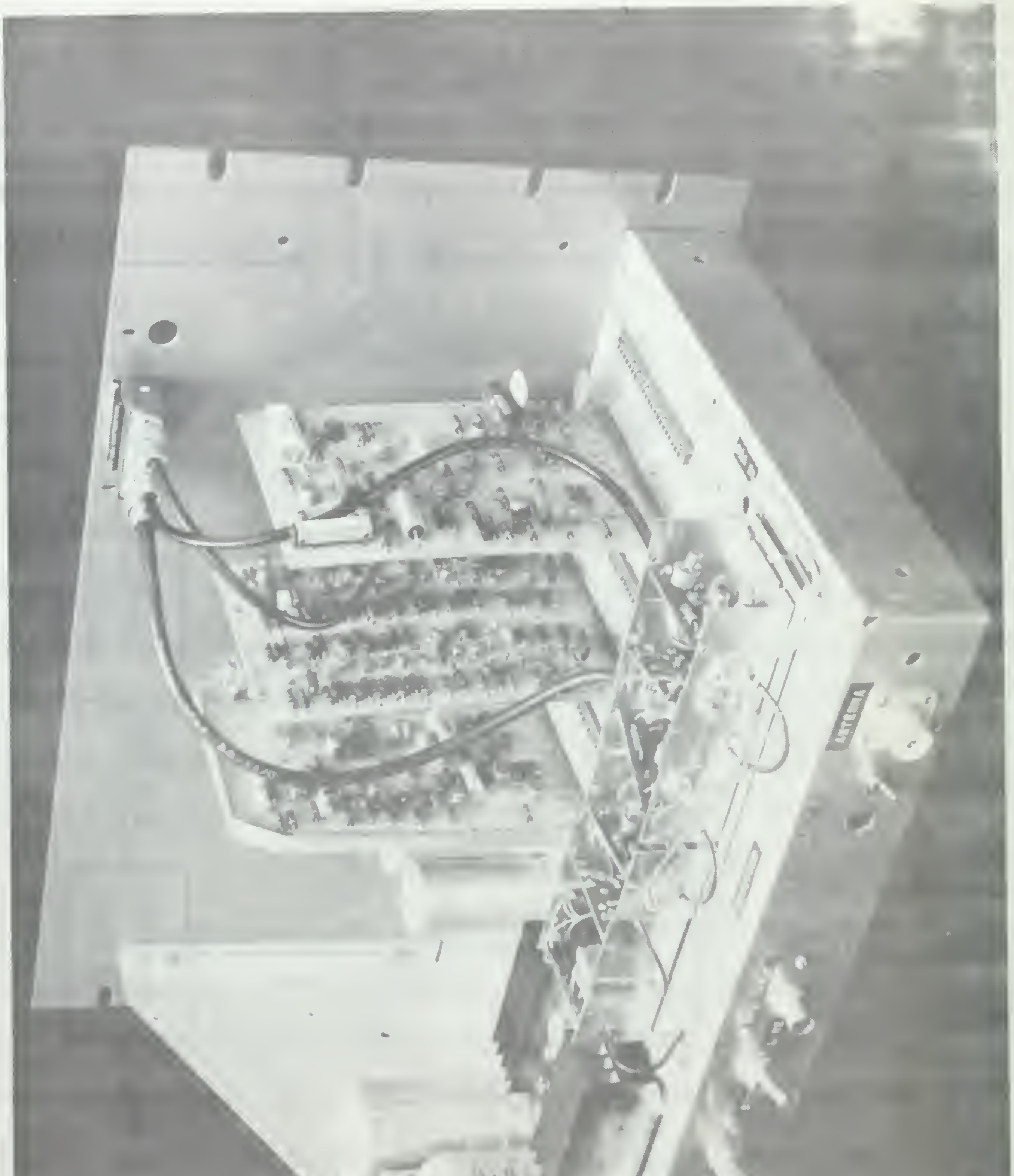


Figure 2.13

For a detailed discussion of this receiver, the tests conducted, and the results obtained, the reader is referred to the thesis by Thomas. Figure 2.13 shows the assembled receiver.

Recommendations for the improvement of this receiver, based upon the performance obtained in the transmitters and Reflex Receiver, are discussed in Section V.

III. THEORETICAL ASPECTS

This section is devoted to defining and discussing some of the factors which affect the accuracy of the proposed navigation system.

A. FREQUENCY ERROR

Frequency error is defined as the difference between the actual frequency (as compared to a primary standard) and the nominal frequency. The contributing factors are termed offset, drift, and deviation.

1. Offset

Frequency offset (α) between two stable oscillators means they operate at fixed frequencies and maintain a constant, usually small, separation. With one oscillator offset from the other, phase accumulates at a constant rate. See Fig. 3.1.

In the laboratory, frequency offset can be measured by a direct-reading frequency-difference meter or by measuring and recording the phase difference between two frequency sources over an extended period of time with a linear phase/ time comparator and recorder [Ref. 8].

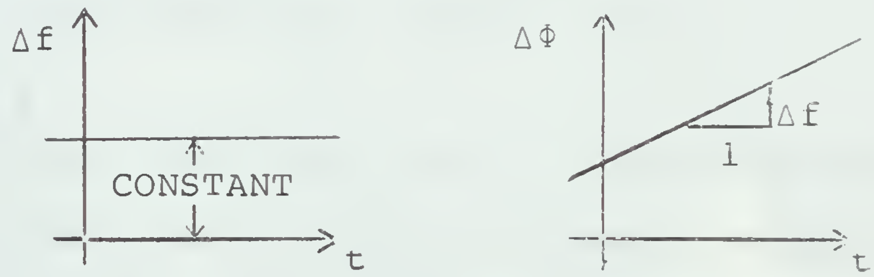


Figure 3.1. Frequency Offset

Since offset rate can be calibrated, this portion of accumulated phase can be predicted and applied to a phase reading as a correction. This correction is theoretically always needed.

2. Drift

Frequency drift (β) can be considered as a rate of change of offset. This means that the frequency difference between oscillators changes with time. An inherent characteristic of crystal oscillators is that after a stabilization period they have nearly a constant rate of increase of resonant frequency with age. See Fig. 3.2. The calibration of β requires much more time (usually > 10 days) than the

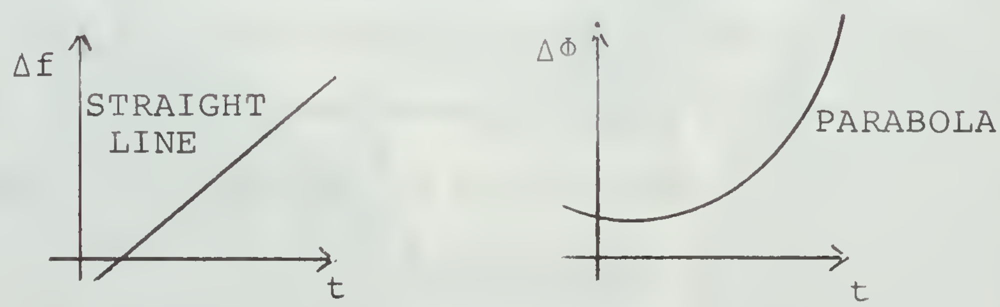


Figure 3.2. Frequency Drift

calibration of α (hundreds of seconds) to obtain comparable accuracy. The results, however, can also be applied to the phase measurements to reduce error. It is possible to obtain crystal oscillators with similar aging rates and minimize this component of error in comparison.

3. Deviation

Frequency deviation attempts to describe the dispersion of frequency about a mean value. Since $\Delta f = d\Delta\Phi/dt$, phase deviation is similarly dispersed about a mean. See Fig. 3.3. This component of error can be caused by

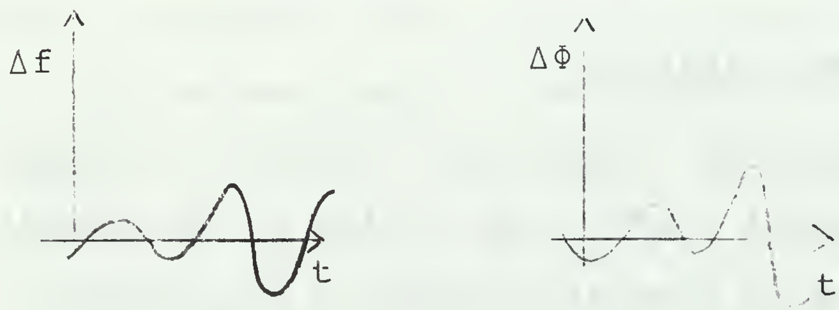


Figure 3.3. Frequency Deviation

temperature or magnetic field variations in Cesium-beam or quartz-crystal oscillators and buffer gas variations in Rubidium-vapor oscillators. This error cannot be predicted and can only be calibrated in a statistical sense. It adversely and directly affects system accuracy and must be minimized.

B. CALIBRATION ERROR

This is the error which results if the system oscillators are calibrated to a frequency other than the nominal system frequency.

The proposed navigation system is based on the ability to compare two oscillators at a nominal frequency and convert change of phase measurement ($\Delta\Phi$) into change of range (ΔR); i.e., $\Delta R = K\Delta\Phi$, where K is the velocity of electromagnetic propagation divided by the nominal frequency and conversion unit constants. For example: if the nominal system frequency is 2.0 MHz and $\Delta\Phi = 180^{\circ}$, then ΔR should equal 75 meters. However, if the system oscillators were improperly calibrated and the transmitted frequency were 2.1 MHz ΔR would be 71.43 meters. This type of error is only mentioned and will not be analyzed since significant calibration error would indicate stable oscillator failure.

C. LONG-TERM STABILITY

The expression "long-term stability" is meant to describe the slow overall trend in the value of the output frequency with time due to secular changes in the resonator, with the assumption that environmental parameters are constant. In practice this instability is expressed in terms of Root-Mean-Square (RMS) Fractional Frequency Deviation (fractional parts per unit of time). For atomic standards, the day-to-day variations about the average may be on the order of a few parts in 10^{2}, but there may be no discernible trend of the average frequency. The day-to-day variations are usually smaller for a good quality crystal standard, but there will be a definite and regular trend in the average output frequency.

D. SHORT-TERM STABILITY

The notion intended to be conveyed by the expression "short-term stability" is quite different than the similar sounding long-term stability. Whereas the latter describes a trend, the former is meant to characterize the statistical property of the fluctuations in the output frequency. A definition of short-term stability is perhaps best made by describing how it can be measured. For example: Using a standard averaging time of one second, a sequence of one-second measurements of the frequency difference between two identical oscillators will yield values scattered about some mean. Short-term stability then, is the RMS, or standard deviation about the mean of the values in this sequence of measurements. To be meaningful, a statement of the averaging time must be included. The longer the averaging time used, the more the deviation is obscured since the average must approach the mean or nominal output frequency in the long run. A complete picture is given when an indication of how short-term stability behaves over a range of averaging times is presented.

In the proposed navigation system, due to the integrating nature of the system receivers, long-term stability is of primary importance. Both terms are defined here only to provide completeness.

E. SELECTION OF A FREQUENCY STANDARD

At the present time, the four types of frequency standards in common use are: the atomic hydrogen maser, the Cesium atomic beam controlled oscillator, the Rubidium gas cell controlled oscillator, and the quartz crystal oscillator. Of these four, the first two are referred to as primary standards and the last two as secondary frequency standards. The

Table IV

Sources of Advantages and Limitations for Frequency Standards

Standard	Principal construction feature	Principal advantage	Principal limitation
Atomic Hydrogen Maser	Active maser with coated wall storage cell having longest atomic interaction time	Great intrinsic reproducibility, long- and short-term stability. Primary standard capability	Size and weight
Cesium Atomic Beam Resonator Controlled Oscillator	Atomic beam interaction with fields--minimum disturbance of resonating atoms due to collisions and extraneous influences	High intrinsic reproducibility and long-term stability. Designated as primary standard for definition of time interval	Short-term stability
Rubidium Gas Cell Resonator Controlled Oscillator	Gas buffered resonance cell with optically pumped state selection	Compact and light weight. Very high degree of short-term stability	Requires calibration against primary standard
Quartz Crystal Oscillator	Piezoelectrically active quartz crystal with electronic stabilization	Very compact, light and rugged. Inexpensive	Long-term stability. Requires calibration against primary standard

distinction is that the primary standard does not require any other reference for calibration, whereas the secondary standard requires calibrations both during manufacture and use, at certain intervals depending upon the stability required. Table IV, which was obtained from Ref. 9, gives a summary of the advantages and limitations for these four types of frequency standards

Probably the most important trade-offs in the selection of a frequency standard for a navigation system are the price versus long-term stability and, of course, the latter's effect on RMS error accumulation. Figure 3.4 shows, in graphic form, the price ranges for present day atomic and crystal frequency standards according to the long-term stability performance expected and the resultant error accumulation.

F. VARIATIONS IN PROPAGATION VELOCITY

Although the effects of variations of the speed of light on the phase stability of the proposed system have not been thoroughly investigated, due to the wavelength used and the relatively short nearly all over-water path of propagation intended, these variations are not expected to introduce significant errors.

G. PHASE MEASUREMENT

The technique of phase measurement used in this system distinguishes between positive and negative changes in phase over a full 360° of phase change. This technique uses

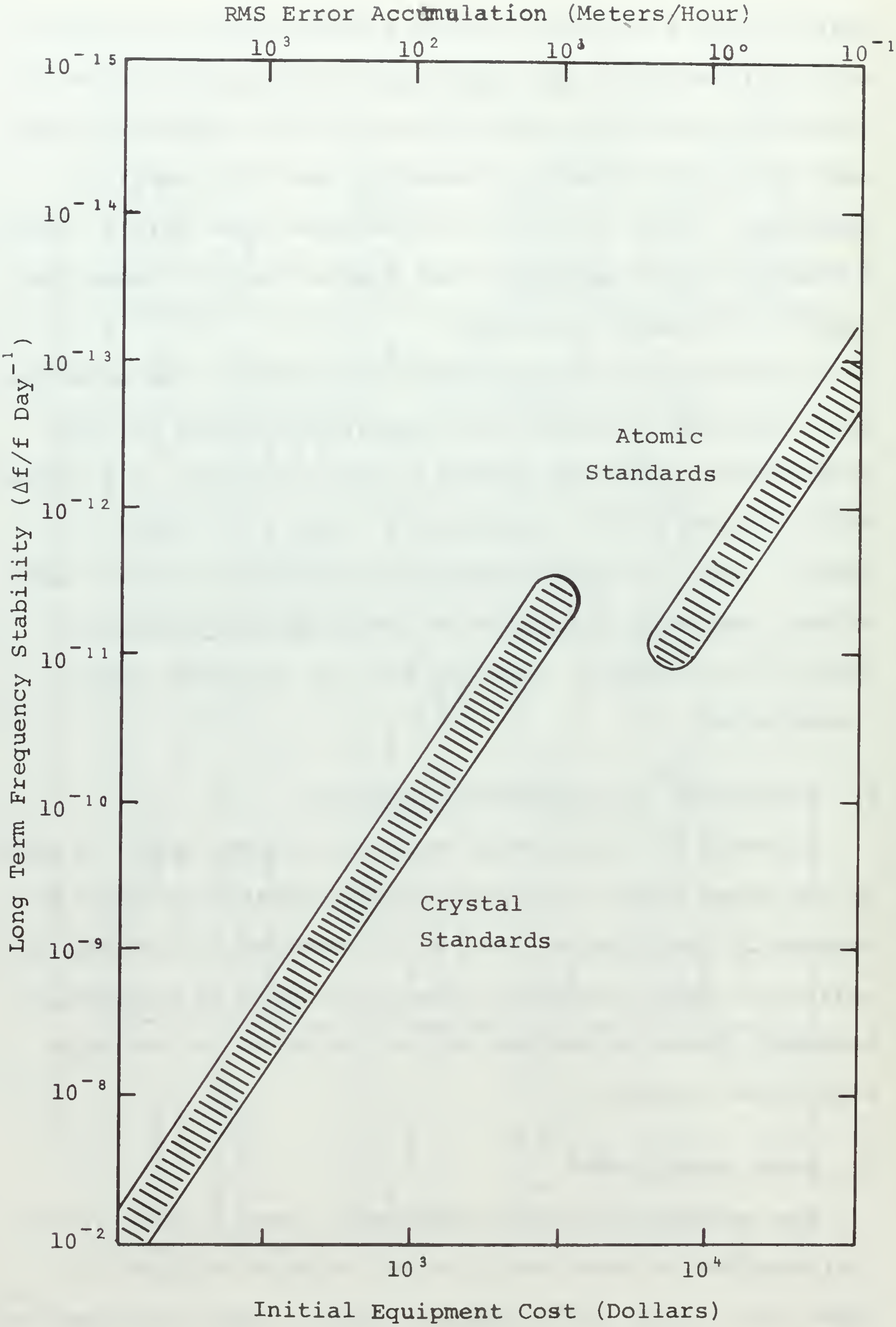


Figure 3.4. Stability vs Cost and Error

the positive-going zero-crossings of the two signals being compared to set and reset a bistable multivibrator (flip-flop). One signal sets the flip-flop to one stable state and the other signal resets the flip-flop to the other stable state. The portion of time the flip-flop is in a given state is an unambiguous measure of the phase difference between the two signals. The phase resolution of this method is limited by the speed of the zero-crossing detectors (Schmitt triggers). Of course, a blind spot does exist as the two signals cross zero together. However, this blind spot has been made to obscure less than a degree of phase.

H. PHASE-LOCKED LOOPS

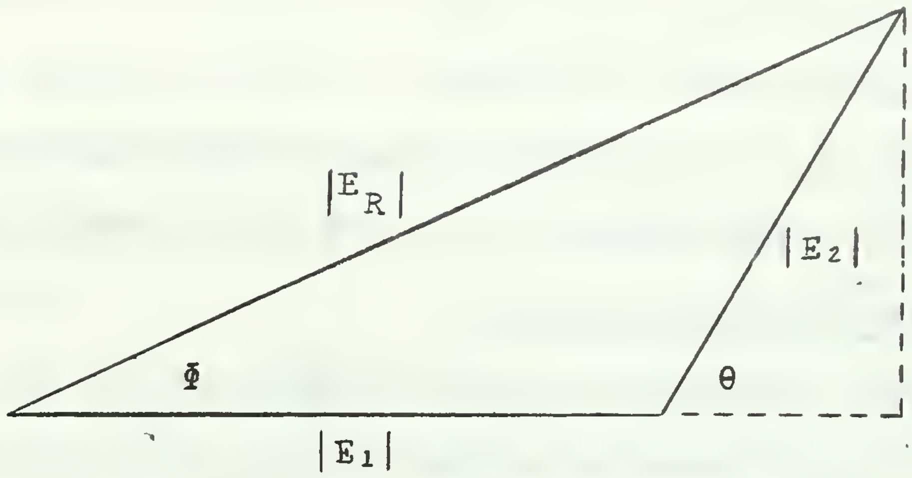
Phase-locked loops in both the transmitters and the receivers are used to maintain phase stability exclusive of changes in components in the linear circuitry. This is complete in the transmitter where signal levels are high enough to assure positive control. In the receivers, however, not all of the linear circuitry can be included in phase-locked loops without severe degradation of receiver sensitivity.

The signal intended for the receiver has a bandwidth of only a few Hertz. None the less, narrow filters and high Q tuned circuits outside the phase-locked loop could cause severe phase distortion with any frequency change. Even though the signal received is very frequency constant, changes in component values in the receiver may cause tuning and corresponding phase changes.

The design of a tuned radio-frequency amplifier providing a low noise figure without phase distortion over a small operating frequency range is necessary for a successful system. The use of a broadband cascade amplifier followed by a crystal filter within a phase-lock loop seemed to meet these requires as applied to the immobile Reflex Receivers.

I. REFLECTION ERROR

Due to the finite propagation velocity of electromagnetic waves, a reflected wave, having a longer path length, will always have a longer transmission time than a direct wave. If the directed wave and the reflected wave are both received, they will add as phasors as shown in Fig. 3.5. The receiver phase detector is quite amplitude level insensitive, so the magnitude of the composite signal received, $|E_R|$, is of no concern as long as it can be detected. Note, however, that the phase of the received signal, Φ, is a function of: direct signal magnitude, $|E_1|$; reflected signal magnitude, $|E_2|$; and the additional pathlength, L. If the magnitude of the reflected wave is much smaller than that of the direct wave, $|E_2| \ll |E_1|$, then the phase distortion is negligible. If the magnitude of the reflected wave approaches the magnitude of the direct wave, $|E_2| \to |E_1|$, consider the worst-case situation where the relative phase of the received wave phasors approaches quadrature, $\theta \approx 90^\circ$. For an allowable phase error of 15°, corresponding to a navigation error of about 6.25 meters at 2.0 MHz, $|E_2|$ must be constrained



$$E_1 = |E_1| \cos \omega_o t \tag{3.1}$$

$$E_2 = |E_2| \cos (\omega_o t + \theta) \tag{3.2}$$

$$E_R = E_1 + E_2$$

$$E_R = \sqrt{(|E_1| + |E_2| \cos \theta)^2 + (|E_2| \sin \theta)^2} \cos \left| \omega_o t + \tan^{-1} \left(\frac{|E_2| \sin \theta}{|E_1| + |E_2| \cos \theta} \right) \right. \tag{3.3}$$

Equations 3.1 and 3.2 describe the electric field phasors of the direct and reflected components of the received electric field phasor described in Eq. 3.3.

Figure 3.5. Phasor Diagram of Received Signal

such that $|E_1|/|E_2| > 4$. Where $|E_1|/|E_2| \approx 3$, the maximum error would be about 8.4 meters. Note that this error is not cumulative; errors in subsequent measurements are equally affected by reflection but not by previous measurements.

1. Sky Wave Reflections

This navigation system is designed to use a resonant vertical whip antenna providing a vertically polarized radiated wave, with a radiation pattern shaped like the top half of a horizontally oriented donut. The pattern can be described by Equation 3.4,

$$E = \frac{K}{D} \sin\alpha \quad , \quad \alpha \in [\, 0^{\circ}, 90^{\circ} \,] \tag{3.4}$$

where α is the angle off the vertical, D is the radial distance from the antenna, and K is a constant antenna parameter.

A sky wave reflection, which can occur from any of several ionospheric layers, produces an electric field phasor expressible as,

$$E_R = R(\, \rho,\alpha \,) \frac{K}{D_R} \sin\alpha \,. \tag{3.5}$$

The parameter K is still constant and D_R is the total distance travelled by the reflected wave. $R(\rho,\alpha)$ is a reflection factor (< 1) which is a function of the normal reflection coefficient, ρ , and the angle of incidence, α . Note that the ionosphere is considered a reflecting surface parallel to the earth's surface resulting in angles of incidence and reflection that are equal to the angle off the vertical for a given ray.

Continuing the worst-case analysis to obtain an expression for the $|E_1|/|E_2|$ ratio as a function of the direct distance, D, between the transmitter and receiver, let h represent the lowest effective height of the ionosphere. Then D_R is expressed as

$$D_R = \frac{2h}{\cos\alpha} . \tag{3.6}$$

Equation 3.5 then becomes

$$E_R = \frac{R(\rho,\alpha) K \sin\alpha \cos\alpha}{2h} . \tag{3.5a}$$

Using equation 3.4, the direct signal at the receiver is given by

$$|E_1| = \frac{K^2}{D} \tag{3.4a}$$

and setting $\alpha \simeq 0$ to maximize E_R the direct distance is given as $D \simeq 2h \tan\alpha$. Hence the direct signal at the receiver becomes

$$|E_1| = \frac{K^2}{2h \tan\alpha} \tag{3.4b}$$

and equation 3.5a yields the reflected signal at the receiver as

$$|E_2| = \frac{R(\rho,\alpha) K^2 \sin^2\alpha \cos\alpha}{2h} \tag{3.5b}$$

Finally, by combining equations 3.4b and 3.5b

$$|E_1|/|E_2| = \frac{1}{R(\rho,\alpha) \sin^3\alpha} . \tag{3.7}$$

Approximate values of $R(1,\alpha)$ obtained from Ref. 4 were used to plot $|E_1|/|E_2|$ as a function of D and α . Figure 3.6 shows the results of this worst-case analysis and the limiting condition where $R = 1$.

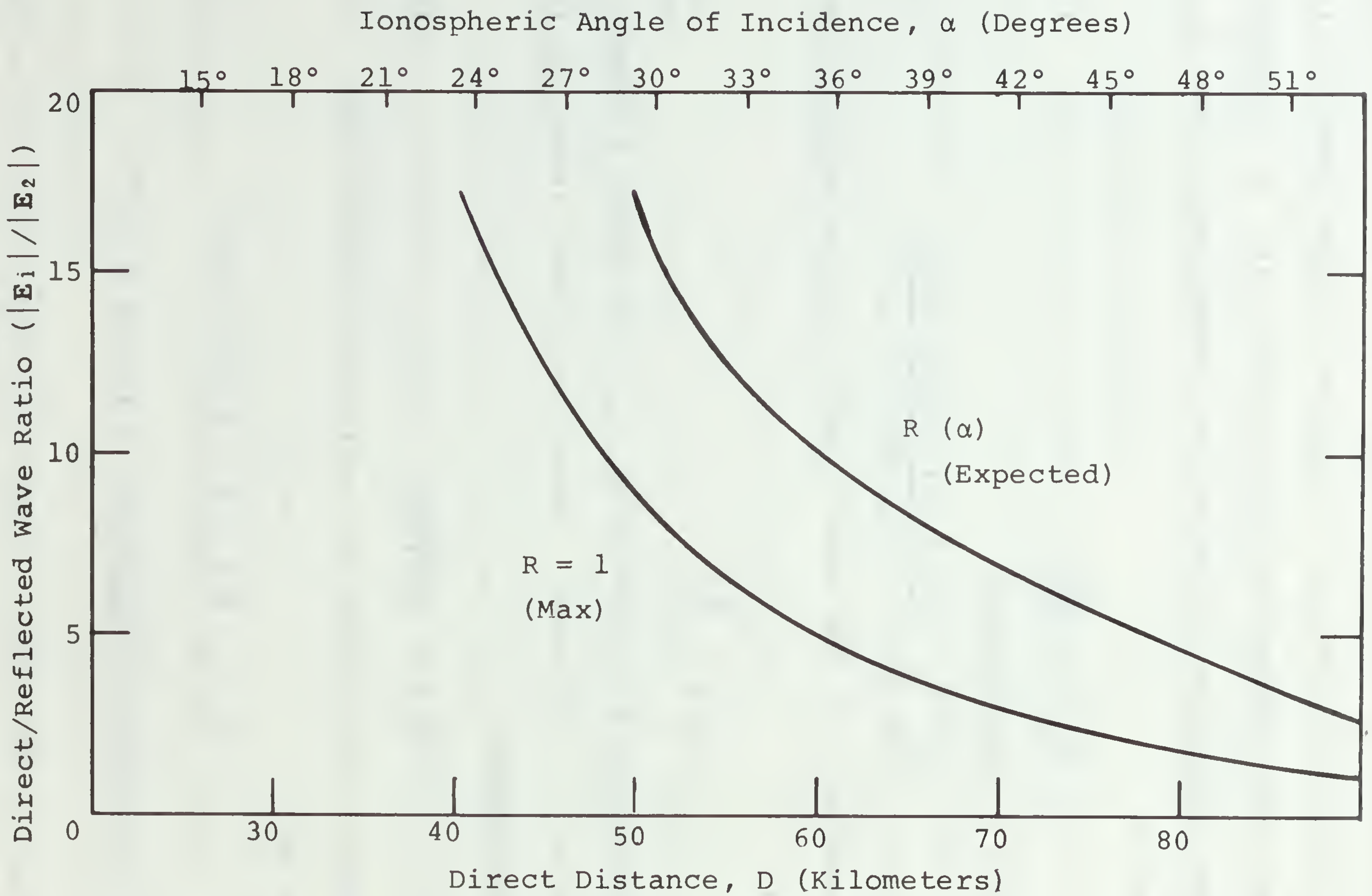


Figure 3.6. Direct/Reflected Wave Ratio

The term $R(\rho,\alpha)$ can be further specified as a function of the ionization level but several inconsistent mathematical models have been tried based on different measured data. The difficulty seems to be that R is an anomalous parameter. For this navigation system, if the maximum ratio is specified as 4, then the phase error due to sky reflections will be 6.25 meters out to ranges of at least 63 kilometers (32 nautical miles).

2. <u>Object Reflections</u>

The same argument about the $|E_1|/|E_2|$ ratio holds for the case where part of the received signal is reflected from an object such as a ship, airplane, or coastline. This type of interference was investigated by Palmer during a study of Loran B [Ref. 10].

J. EFFECTS OF NOISE

Since the receivers employ narrow-band quartz-crystal filters, they are in effect correlation detectors for all sine-wave signals in the passband. Therefore, because the receivers integrate the signals over many cycles, noise does not affect the phase measurement and the signal-to-noise ratio can be less than one. This allows the transmitters to operate at very low power levels with no degradation of service.

K. ERROR ANALYSIS

The errors affecting this navigation system are divided into three broad categories; random errors, systematic errors, and mistakes or blunders.

1. <u>Random Errors</u>

Random errors are unpredictable in magnitude and sign and are governed by the laws of probability. For practical purposes, these errors will be considered to fall on either side of an arithmetic mean value, and are plotted as bands of tolerance, ε , about a measured range.

a. Single Line of Position

Given a measured range within a tolerance $\pm\varepsilon$ the actual position is bound by a band of width 2ε . See Fig. 3.7.

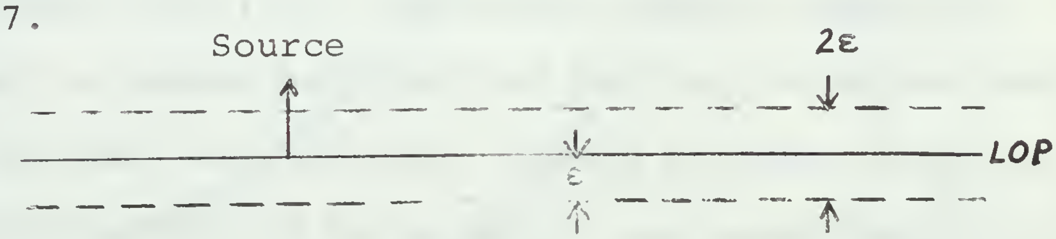


Figure 3.7. Single Line of Position

b. Double Lines of Position

Given two range measures and assuming that the errors are independent, uncorrelated, the greatest position deviation, δ , from the intersection of the lines of position is given by

$$\delta = \sqrt{a^2+b^2+2ab\cos\theta}\ , \tag{3.8}$$

where $|a| = \dfrac{\varepsilon_1}{\sin\theta}$ and $|b| = \dfrac{\varepsilon_2}{\sin\theta}$. In vector form Equation 3.8 can be expressed as $\delta = a + b$. See Fig. 3.8. In the special case where $\varepsilon_1 = \varepsilon_2$ the greatest position

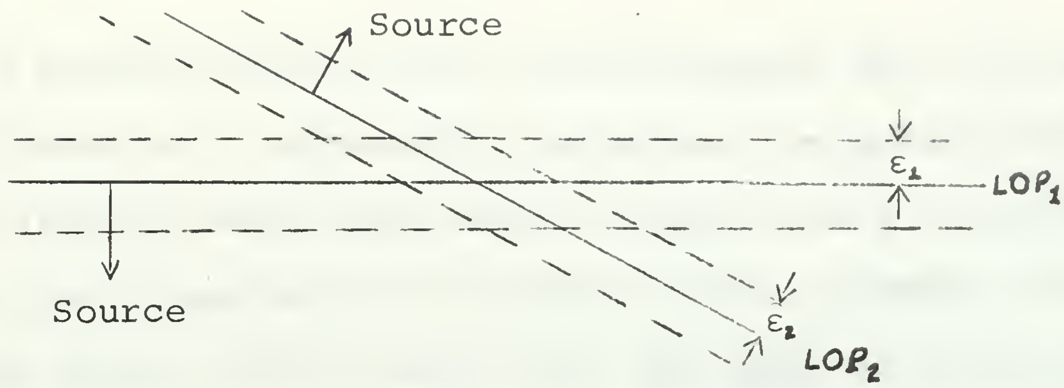


Figure 3.8. Double Lines of Position

deviation becomes:

$$\delta = \frac{2\varepsilon \cos\frac{\Theta}{2}}{\sin\Theta} . \tag{3.9}$$

Typical maximum position error is expressed as:

$$\delta \geq \sqrt{2}\ \varepsilon_{largest} . \tag{3.10}$$

Table V shows typical values of δ when $\varepsilon_1 \simeq \varepsilon_2$.

Table V

Position Deviation

Θ	90°	80°	70°	60°	50°	40°	30°	20°	10°	5°	0°
δ	1.4ε	1.6ε	1.7ε	2.0ε	2.4ε	2.9ε	3.9ε	5.8ε	11ε	23ε	∞

Note in Table V, that even when the line of position error is small, if the angle of intersection is small the possible position error is enormous. For $\varepsilon_1 << \varepsilon_2$ the position deviation approaches 1/2 the values given in the Table.

c. Triple Lines of Position

Most navigators use a third line of position for confirmation. If there were no random errors this would be redundant. Not only does a measurable error nearly always exist, but the responsibility for safe and precise navigation dictates using all available information. In practice, each position is fixed with at least three lines of position. Typical examples shown in Fig. 3.9 illustrate the areas of probability of position. The cross-hatched areas show the region of higher probability of location. In the event that one line of position is unusable, the remaining regions indicated show the regions of lesser probability. These regions of lesser probability can be analyzed exactly as indicated for double lines of position.

As seen in Fig. 3.9a, the most compact region of highest probability occurs when the lines of position form mutual intersecting angles of sixty degrees at a common point. Figure 3.9b illustrates that the region of highest probability does not always exist.

The intersection of three lines of position can be analyzed mathematically although it is more involved than for two lines. The reader is directed to Ref. 3 for this analysis.

2. Systematic Errors

Systematic errors are those which follow some definite pattern or law and thus are correlated. In this system the phase offset of the Mobile Receiver Oscillator with respect to all the transmitters is a constant for any instant of time and may be approximated as constant over the short measurement cycle.

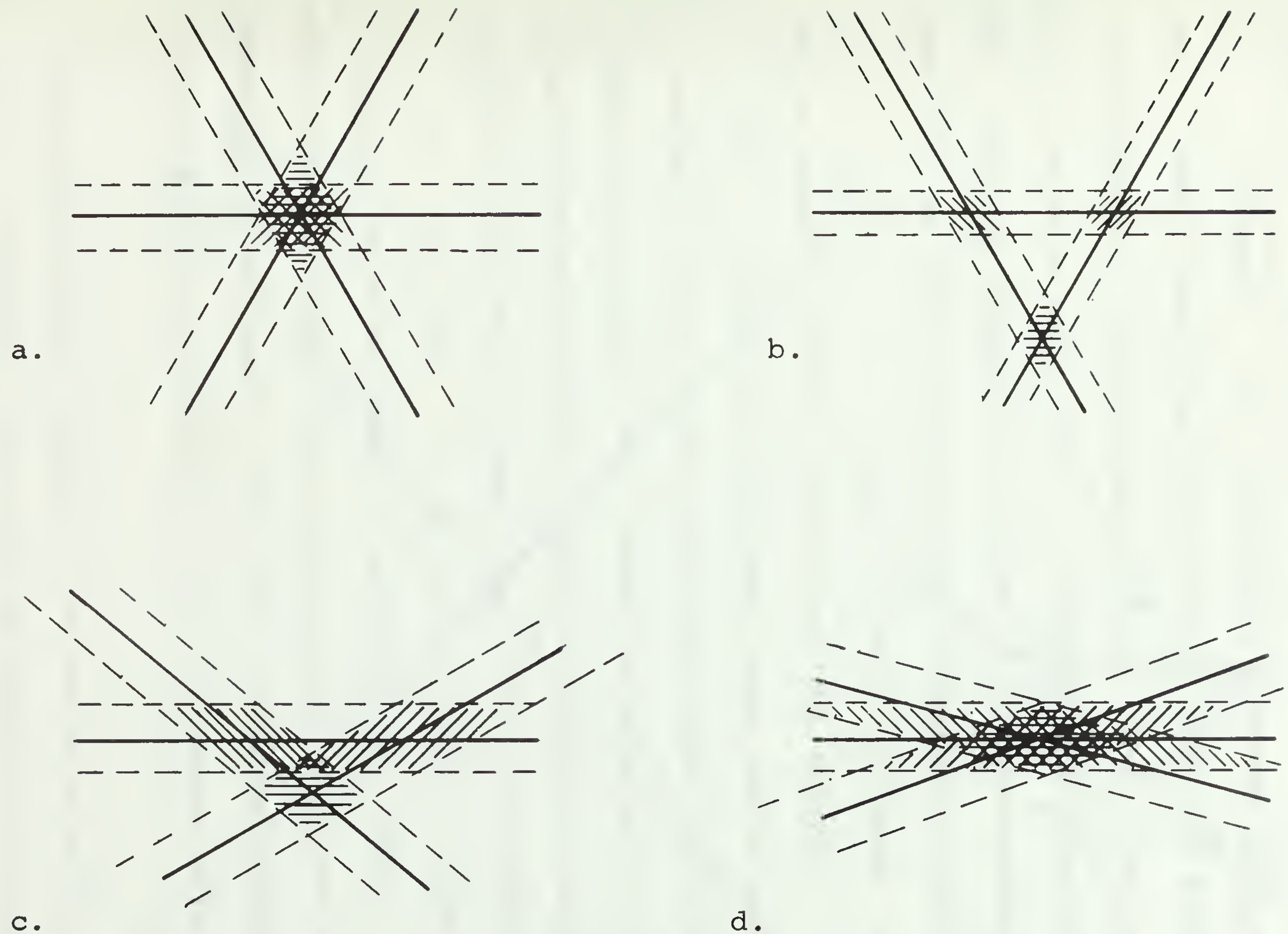


Figure 3.9. Triple Lines of Position

Since this error is correlated, the position error analysis illustrated above is no longer valid and new approaches are necessary. In this analysis the third line of position is not redundant, but must exist to calculate the systematic error present, and thus determine a fix. Therefore, it will be assumed that three transmitters are phase locked to one reference oscillator, and that the receiver is monitoring their sequential transmissions. First, the receiver location will be considered fixed. With the analysis technique clear, the additional problem of receiver motion will be discussed.

a. Receiver Location Fixed

Suppose that as a result of one or more of the factors that affect phase stability, an error, ε, is introduced as an additional phase shift in the receiver. Since all of the received signals are identical, the additional phase shift will be added to each phase measurement and a triangle, $P_{12}P_{13}P_{23}$, will result from the intersection of range arcs $R_1 + \varepsilon$, $R_2 + \varepsilon$, $R_3 + \varepsilon$. See Fig. 3.10.

Since the receiver is known to be at only one point, the navigator may converge the triangle to this point by successively moving all the arcs of position in the same direction with respect to their transmitter until a point is formed.

The trial and error method of moving arcs can be alleviated by applying an arbitrary increment, δ, to each original measurement, forming a second triangle, $P'_{12}P'_{13}P'_{23}$. Connecting points P_{12} and P'_{12} to form line

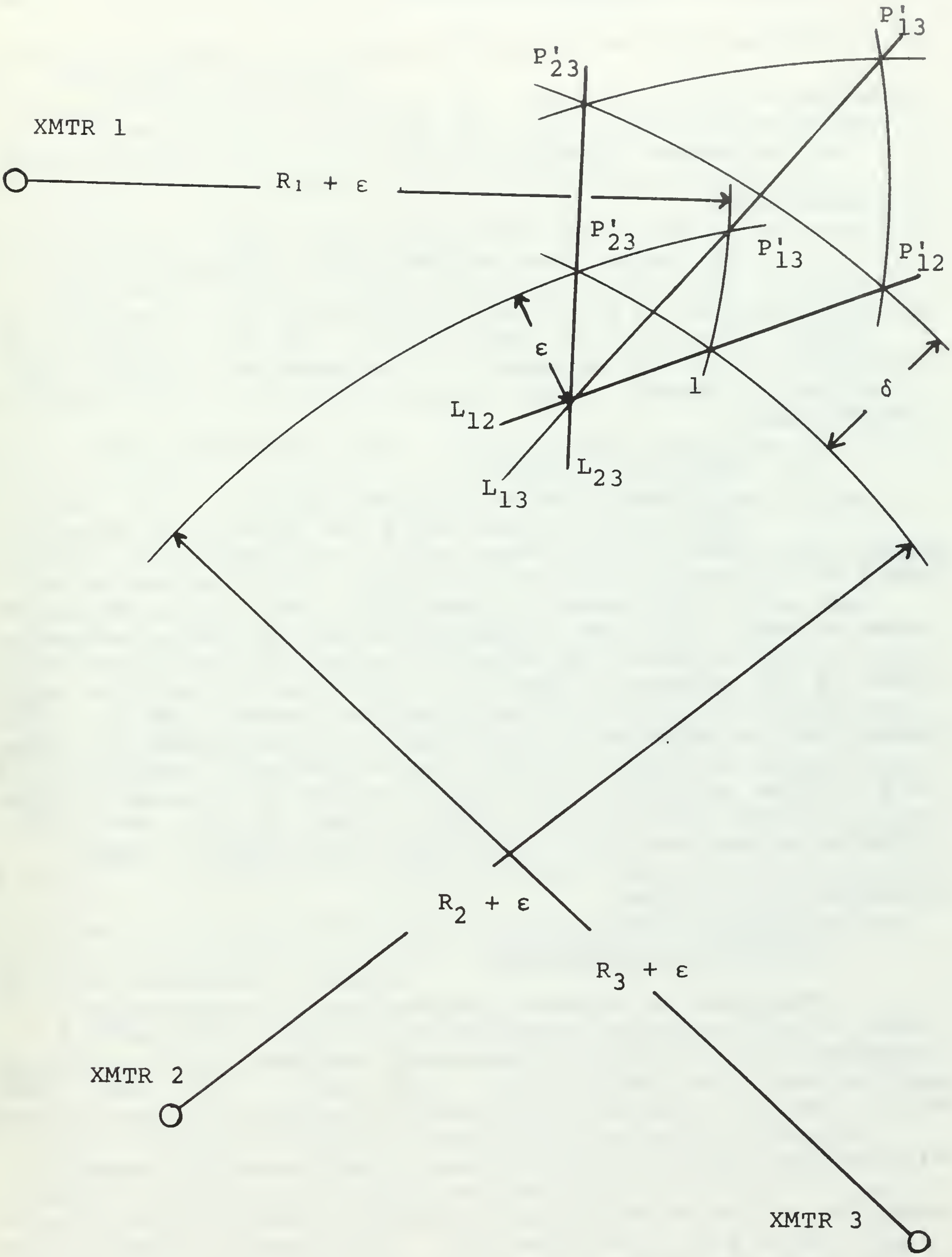


Figure 3.10. Systematic Error Correction

L_{12} and similarly forming line L_{23} from points P_{23} and P'_{23} provides the two required lines that intersect at the convergence point desired. To check the construction, line L_{13} can be passed through points P , P' , and the point of convergence.

Of course, the perpendicular distance from any original arc of position to the point of convergence is precisely the error in phase, ε , between the receiver and transmitters.

b. Receiver in Motion

Since the receiver does not make range measurements of all receivers simultaneously, relative motion towards or away from some transmitters during the measurement cycle is the general situation. Each line of position must, therefore, be advanced or retarded to a designated fix time. This is done on the basis of rate of change of phase in the received signal and does not require knowledge of the receivers true speed.

3. Mistakes or Blunders

Mistakes or blunders can be due to carelessness, transposition of figures, incorrect readings, poor plotting, etc. Careful checking and working a problem by other methods will correct most of these errors. Additionally, careful planning in the presentation of data is essential in eliminating the true source of most of the commonly made mistakes.

IV. TESTS AND RESULTS

A. OSCILLATOR STABILITY

The oscillators provided for the initial development of this system were the Sulzer Laboratories Model D-5 oscillators. These are solid-state units which provide a 5.0-MHz output with a rated long-term stability of five parts in 10^{10} per day. The crystal is an AT-cut, fifth-overtone, contour-ground, plated quartz resonator mounted in an evacuated metal bulb. Temperature stability to within $.01^{\circ}C$ is provided by double proportional ovens. Several investigations of the stability of these oscillators have been made. Most prominent of these tests were the shock and vibration tests conducted by Austin reported in Ref. 11. As a result of these tests, it was concluded that for 10-second intervals after moderate physical shocks the drift rate ($\Delta f/f$) for all three oscillators was less than 1×10^{-11}. Further, it was concluded that after six months of aging the drift rates were satisfactory for evaluation of this navigation project.

A long-term stability measurement was made from 24 February 1969 until 16 May 1969. Comparisons were made against a Varian Model V-4700 Rubidium Vapor Frequency Standard having an advertized long-term stability of 5×10^{-11} per year (standard deviation). The results of this 82-day test period are tabulated in Table VI.

Table VI

Oscillator Stability

Sulzer Ser. No.	19	22	25
Drift Rate ($\Delta f/f$)	3.5×10^{-11}	2×10^{-11}	1.5×10^{-11}
Error from Straight Line Prediction	1 Cycle	4 Cycles	1 Cycle

At the end of 82 days, the two Sulzers Ser. Nos. 19 and 25 were compared. The error over the interval was less than 2 cycles, corresponding to a maximum error of 300 meters at the comparison frequency of 100 KHz.

After four years of nearly continuous operation, aging still causes these oscillators to increase in frequency. This increase has stabilized at about 1/10 the advertised stability and is quite predictable, so does not seriously degrade the navigation accuracy.

B. OSCILLATOR CONTROL

Prior to conducting tests with the complete Reflex Control Transmitter, Sulzer Ser. No. 25 was tested with a Digital-to-analog converter over a 3.5-volt range. Very good control was observed with input voltages as small as 0.3 volts. The internal varactor circuitry of the Sulzer is advertised to provide an output change of 1×10^{-8} for a 1.0 to 7.0-volt dc range, with a sensitivity of 1×10^{-9} per volt. This proved to be very adequate for use in the Reflex Transmitter and is much superior to manually synchronizing the oscillators.

C. CONTROL TRANSMITTER STABILITY

During initial tests of this transmitter, it was noted that the input impedance changed as the transmitter was turned on. Using the VCO previously designed for the system by Thomas, the impedance change was sufficient to "pull" the VCO frequency. On a communication receiver, set for CW operation, a "zing" was heard at the commencement of each transmission. Since the oscillation voltage was present across a varicap diode, as well as the controlling dc voltage, there was a tendency for the VCO to distort its output.

A new type of VCO and buffer designed to prevent this malfunction is shown in schematic form in Fig. 4.1. In the

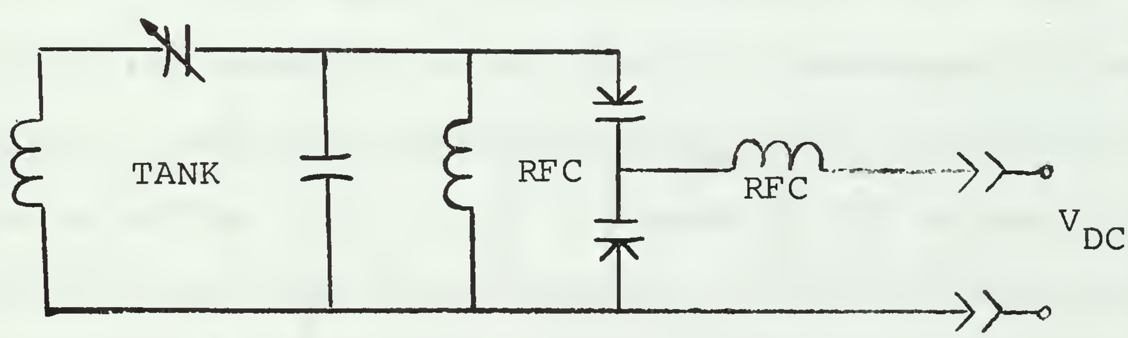


Figure 4.1

Balanced Voltage-Controlled Oscillator

new design, two varicaps are placed so that they are in series back-to-back in the oscillator resonant circuit, but in parallel in the dc control circuit.

The fixed capacitor, shown in the circuit, only serves to narrow the tuning range of the varicaps and preserve the Q of the circuit. In the actual circuit, the RF chokes were replaced by high resistances. In this circuit, the effect of the oscillator voltage to reduce the capacitance of one diode is offset by an increase in the other. This has a tendency to balance out any distortion and still maintain full control-voltage effect.

Although this VCO provided equally excellent phase stability with some improvement in temperature immunity, a small "zing" can still be heard.

D. REFLEX TRANSMITTER STABILITY

Since a good bit of the practicality of this system is based on the ability to obtain phase lock of the Reflex Oscillator to the Control Oscillator, it was gratifying to see the excellent tracking that this unit obtained.

The test consisted of using Sulzer Ser. No. 19 as the Control Oscillator with the Control Transmitter working into an equivalent 6-ohm load of carbon resistors. Coaxial leads were used as the propagation path to the Reflex Receiver. The output of the Control Oscillator provided the reference to one side of a Relcom Balance Mixer, used here as a phase detector. Sulzer Ser. No. 25 was used as the Reflex Oscillator. The output of the Reflex Transmitter was led to the other side of the Relcom. Using a strip chart recorder connected to the output of the Relcom, phase resolution of less than a degree was readable. With the exception of a variable overshoot as the Reflex Transmitter VCO established lock with its oscillator, no loss of phase lock was discernible. This test configuration is shown in Fig. 4.2.

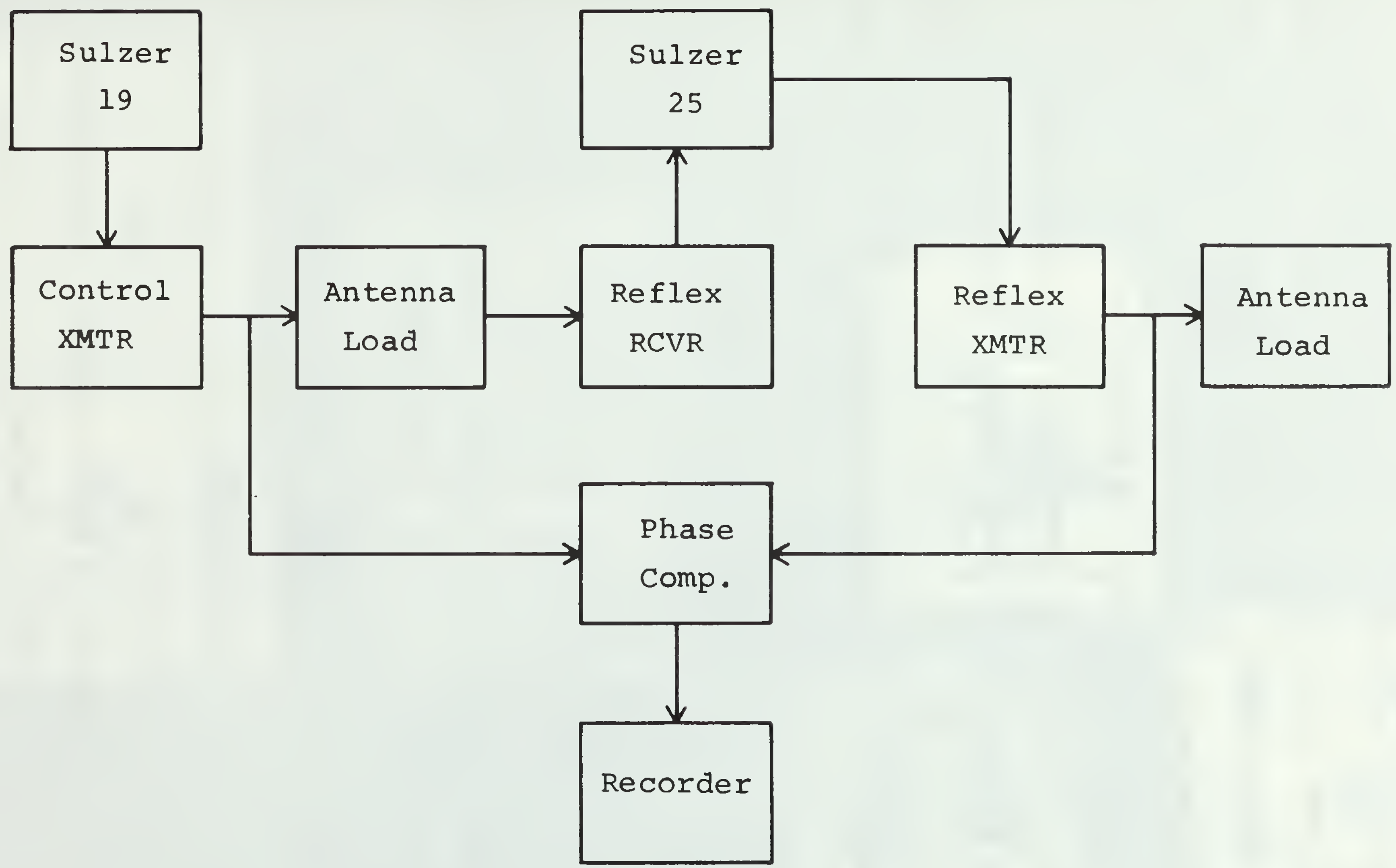


Figure 4.2. Transmitter Stability Test Configuration

E. ANTENNA

Since the system is to be operated in an environment where portability is important, whip antennas were planned for use on both transmitters and receivers. This also allows the use of one antenna in the Reflex Receiver/Transmitter configuration. Tests were conducted using a commercial Marine band (2-3 MHz) whip antenna with an overall physical length of 20 feet, including an 18-inch center section of inductance for loading. The antenna was mounted on a image plane providing an antenna length of 15.36 meters.

The approximate radius of the near field is then given by

$$R = 2L^2/\lambda = 3.15 \text{ meters.} \qquad (4.1)$$

Preliminary field strength measurements were taken from 38 meters which is well into the far field. A radiation efficiency of 55% was obtained with the antenna driven by a breadboard mock-up of the Control Transmitter. The antenna impedance was measured to be 6-j620 ohms.

V. CONCLUSIONS AND RECOMMENDATIONS

The Control Transmitter developed for this system, as shown in block diagram in Fig. 2.1, was constructed on three circuit cards. Figure 5.1 is an exploded view illustrating this construction. With the exception of the small "zing" previously mentioned, this transmitter has operated flawlessly for several months providing nearly 5.0 watts of RF

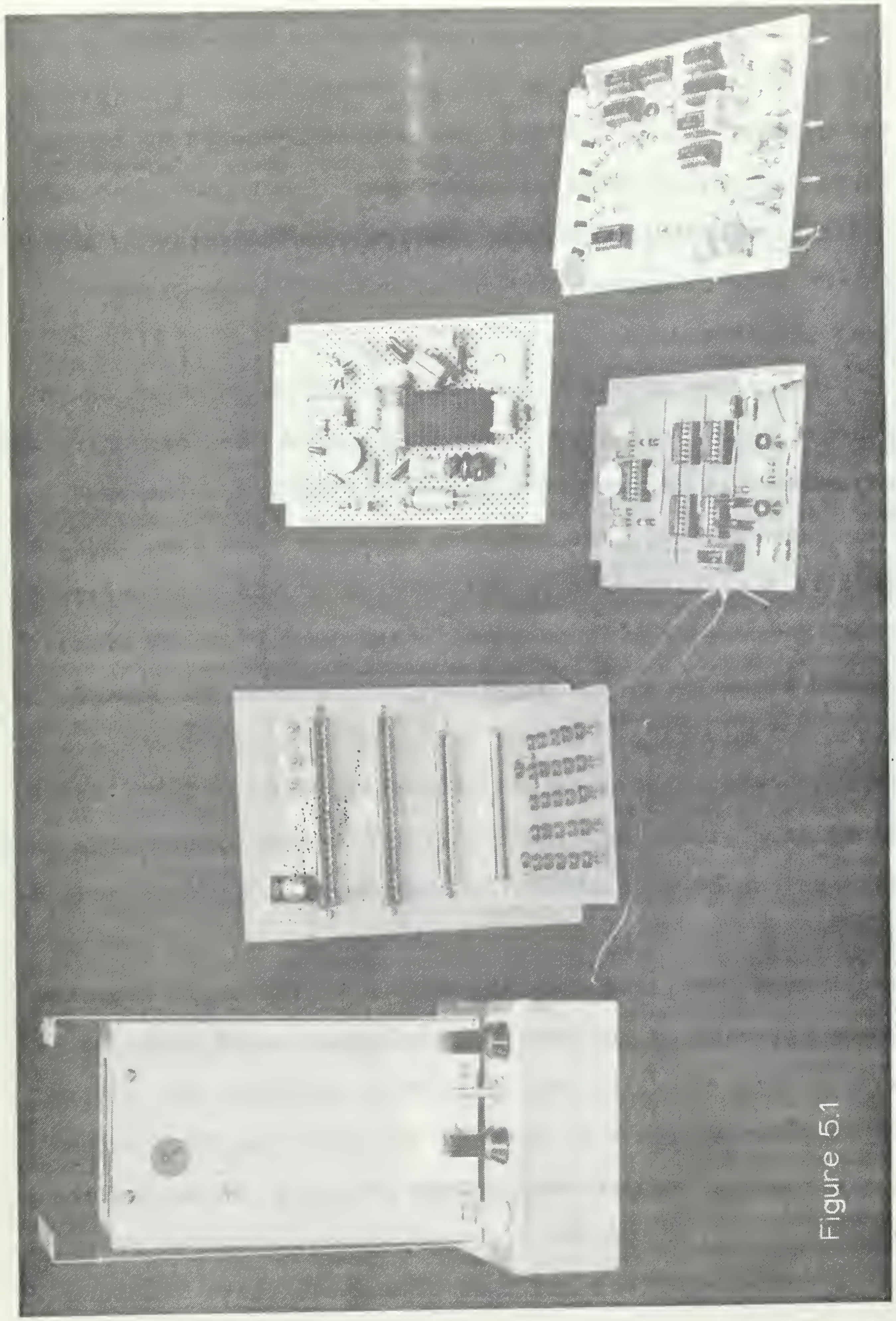


Figure 5.1

output power to a 6-ohm load. The only effect this VCO tuning "zing" has on system operation is that phase comparison must be delayed about 500 ms after initially receiving the signal. Since the VCO is somewhat affected by temperature variations of several degrees, proper packaging for continuous operation should provide some temperature stabilation and, of course, stand-by power for the selected frequency standard.

The Reflex Receiver and Oscillator Control Card shown schematically in Fig. 2.9 required a good deal of tuning and adjustment to obtain the phase-lock stability mentioned in the last section. The receiver circuits need some improvement in sensitivity to be utilized at the 50-mile outer range proposed for this system. The lowest usable signal seemed to be about 5 μV. Although this receiver lacked large dynamic range, proper mixing action to achieve a good IF signal could be obtained by adjusting the 3.0-MHz local oscillator signal amplitude. If the Reflex Transmitter units were relocated frequently, an AGC circuit should be considered. During the phase-lock stability tests, the 64.0-MHz oscillator providing counting pulses to the shift register could not develop the full 1.0-V trigger level required. As a interim measure, the oscillator frequency was lowered to 32.0 MHz at 1.0-V output and the last flip-flop of the shift register was shorted. This provided the equivalent ambiguity correction for frequency division by two prior to phase comparison, but the 1/32 of a cycle phase resolution

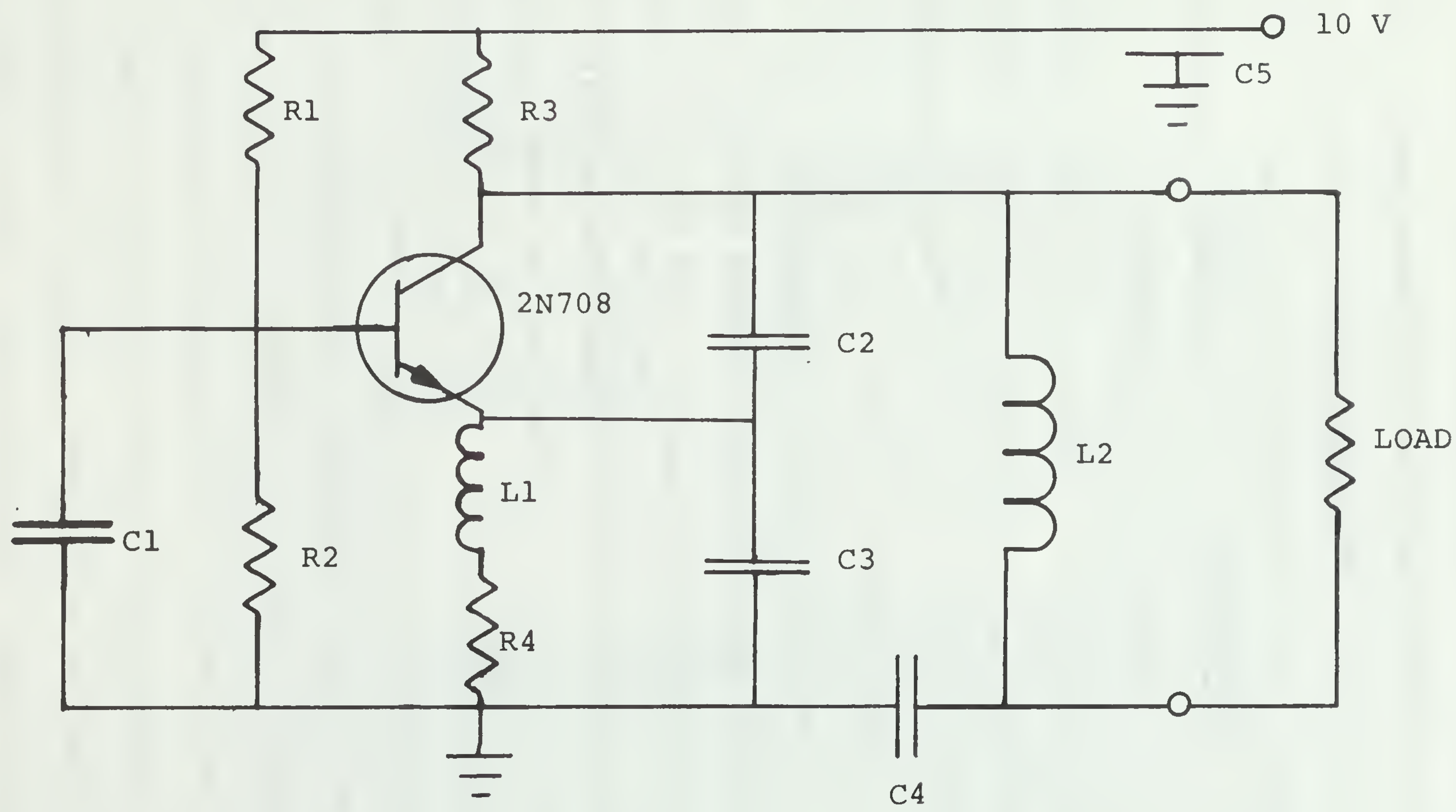


Figure 5.2. Redesigned 64.0 MHz Oscillator Schematic

Table VII

Redesigned 64.0 MHz Oscillator

Components List

Component	Value
R1	1000 Ω
R2	620 Ω
R3	560 Ω
R4	510 Ω
C1	300 pf
C2	30 pf
C3	120 pf
C4	1000 pf
C5	500 pf
L1	25 μh
L2	3 turns No. 18, enameled copper wire, on 1/2 in. dia.
LOAD	1000 Ω (approx. input imped. of IC's used.)

yielded an unsatisfactory signal for stable oscillator control. The redesigned 64 0-MHz oscillator is shown in Fig. 5.2. The Colpitts connection was selected for this frequency because it yields values of tank inductance and capacitance which are fairly insensitive to transistor parameter variations. Note that high stability is not required in this oscillator to provide nearly constant 1/64 of a cycle phase resolution. An exploded view of the Reflex Transmitter unit is provided in Fig. 5.3.

The Mobile Receiver designed for this system was modified with the addition of a preamplifier to increase sensitivity, but it has yet to receive a signal using the antenna proposed for the system in a mobile configuration.

The next step necessary in the development of this system would seem to be in further improving and completely testing this receiver. The major recommendation in this improvement is the addition of an electronic phase-shift network. This network would provide the necessary means of correcting the receiver reference phase for: initial phase offset between the Control Oscillator and the Receiver Oscillator, slow phase shifts in the receiver due to linear circuit component changes, and linearly increasing phase error due to frequency offset between the Control Oscillator and the Receiver Oscillator. The success of this network would allow greater latitude in the improvement of the preamplifier and amplifier stages for necessary signal sensitivity with less concern over inherent phase shifts through these circuits. With the

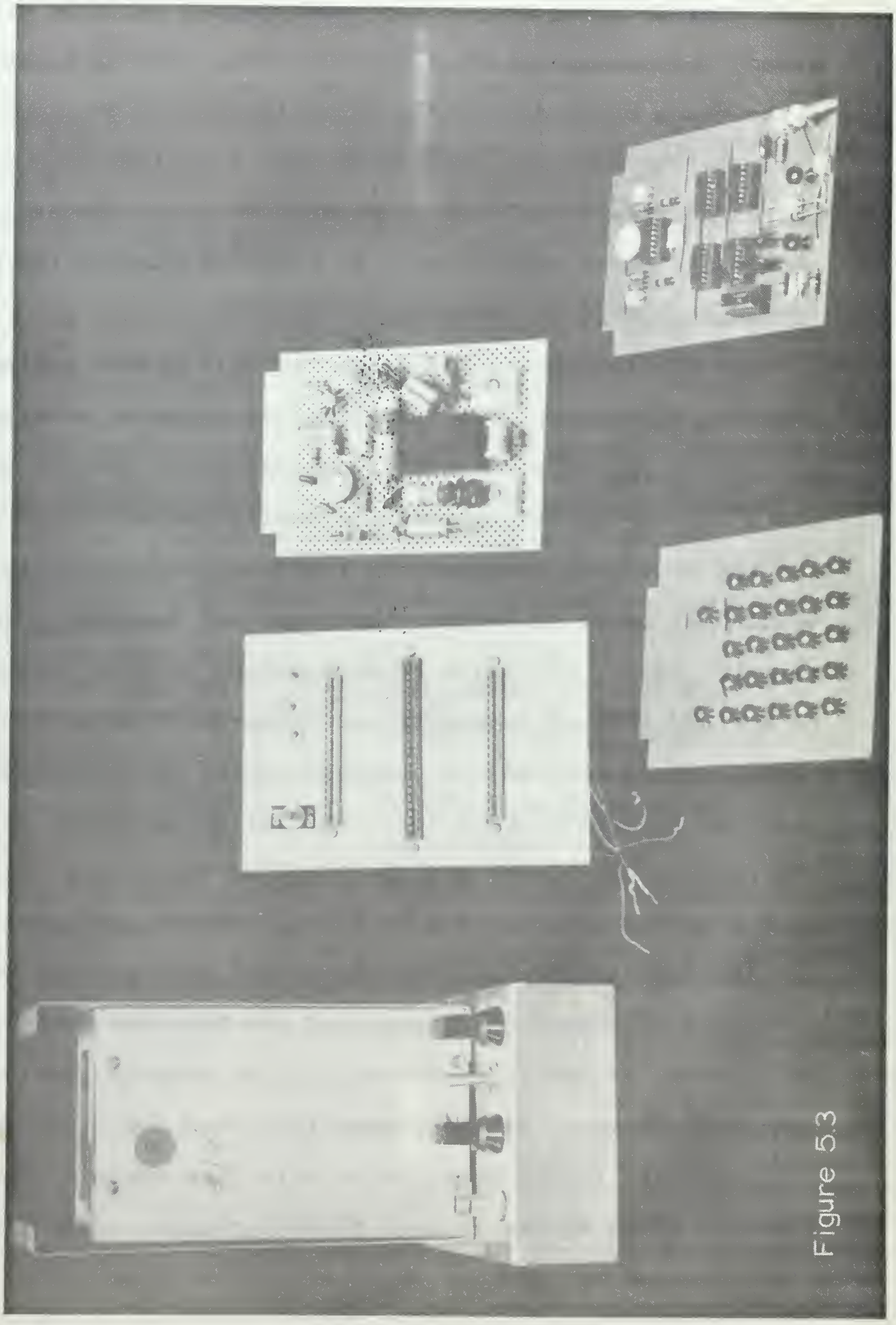


Figure 5.3

correction of phase shifts possible, direct amplification and frequency division might prove more satisfactory than mixing to obtain the desired IF, phase-comparison frequency. The success in the use of integrated circuits in the Reflex Receiver and their widespread use throughout the industry would suggest that this approach be used in any rebuilding of the present Mobile Receiver.

BIBLIOGRAPHY

1. Dean, J. G., An Experimental Investigation of Some Aspects of Frequency Stability in a Proposed Short-Range, Precise Navigation System, M.S. Thesis, Naval Postgraduate School, June 1967.

2. Thomas, N. M. III, Receiver Design for a Short-Range, Precise, Navigation System, M.S. Thesis, Naval Postgraduate School, December 1967.

3. Stenberg, T. R., "Errors and Accuracy of Position, LOPS, and Fixes," Navigation: Journal of the Institute of Navigation, Vol. 10, No. 4, p. 379-394, Winter 1963-64.

4. International Telephone and Telegraph Corporation, Reference Data for Radio Engineers, 5th ed., October 1968.

5. Sulzer Laboratories, Division of Tracor, Inc., Instruction Manual for Model D-5 Oscillator, 621 Lofstrand Lane, Rockville, Md., July 1965.

6. Steinbach, D. L., "IC Frequency Dividers and Counters," Parts 1 and 2. Electronics World, p. 32-39, December 1968 and p. 49-55, January 1969.

7. Bartee, Thomas C., Digital Computer Fundamentals, 2d ed., McGraw-Hill, 1966.

8. Oliphint, R. E., "Transporting Time," On Frequency, v. 1, No. 4, September 1969.

9. Hewlett Packard Company, Measurement - Analysis - Computation, p. 637, 1969.

10. Palmer, W. (n), Final Engineering Report on Loran B Reradiating Structures and Station Siting Criteria, USCG Contract Tcg 40789 ITT Laboratories, 500 Washington Ave., Nutley, N.J., 1961.

11. Austin, D. R., An Experimental Investigation of the Effects of Position and Motion on the Frequency Stability of Certain Crystal Oscillators, M.S. Thesis, Naval Postgraduate School, 1965.

12. Kraus, J. D., Antennas, McGraw-Hill, New York, 1950.

13. Davies, K., "Ionospheric Radio Propagation," National Bureau of Standards Monograph 80, 1 April 1965.

14. McKay, J. D., and Preston, G. L., An Investigation of Factors Which Degrade Phase Accuracy in a VLF Navigation System, M.S. Thesis, Naval Postgraduate School, December 1966.

15. Farmer, D. J., "Selection of a Frequency Standard," On Frequency, v. 1, No. 1, January 1969.

16. Berkowitz, R. S., Modern Radar Analysis, Evaluation, and System Design, p. 317-377, Wiley, 1965.

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13. ABSTRACT

A precise short-range relative navigation system has been proposed to provide repeatable position-determining capability of uniform accuracy over the entire area of coverage. It is a continuous-wave phase comparison system, which derives range information from the change in phase between stable oscillators as the distance between them is varied. The transmitters and their associated controls were designed to implement a prototype system. Considerations necessary in the development of the system receiver are discussed based on tests conducted on the transmitters.

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Continuous-wave Phase Comparison, Short-range, Precise						
Navigation System						
Multi-transmitter, Time-multiplexed, Frequency-locked System						
Long-term Stability						
Short-term Stability						
Phase Comparison						
Frequency Error						
Random Errors						
Systematic Errors						
Error Correction						